



Shoreline Position (1D) and Coastal Topographical (2D) Change Monitoring at Gateway National Recreation Area

2012-2017 Trend Report

Natural Resource Report NPS/NCBN/NRR—2018/1739



ON THE COVER

Upper: Oblique photo of Critical Zone Post-Hurricane Sandy at Sandy Hook Gateway National Recreation Area, November 5, 2012. Photo Credit: USGS, Morgan, K. L. M. November 5, 2012. Lower: Oblique photo of Critical Zone at Sandy Hook Gateway National Recreation Area, October 6, 2014. Photo Credit: USGS, McManus C. October 6, 2014.

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Executive Summary

The Trend Report summarizes the results of shoreline position and coastal topography surveys conducted from Spring 2012 through Spring 2017 at sites within Gateway National Recreation Area. Gateway National Recreation Area is made up of three units: Sandy Hook Unit, Jamaica Bay Unit (Breezy Point, Plumb Beach), and Staten Island Unit (Great Kills, Miller Field, Fort Wadsworth). Shoreline data sets include a spatial depiction and statistical data of annual changes and 5-year changes in shoreline position as well as a longer-term trend analysis incorporating the full shoreline dataset, all following the model presented in Psuty et al. (2010b). Coastal topography datasets include profiles of survey data collected annually, annual change metrics, net change metrics, as well as an alongshore depiction of net change, following the model presented in Psuty et al. (2012).

This 2012 to 2017 Trend Report is the first Gateway National Recreation Area Trend Report to incorporate both shoreline and coastal topographical change data. Due to the variable exposure to incident waves influencing inputs of sediment to the alongshore transport system in the various units from updrift sources, there was no common direction of shoreline displacement or profile change throughout the Gateway National Recreation Area Parks. Engineering structures along the beach and adjacent to inlets altered the shoreline position and coastal topography responses in much of Gateway National Recreation Area. Generally, the largest vectors of shoreline change and changes in coastal topography were produced by natural impacts such as storms (e.g., Hurricane Sandy and subsequent winter storms) and by anthropogenic impacts such as beach nourishment or dredging.

All shorelines and coastal topography profiles surveyed during the 2012 to 2017 period were eroded by Hurricane Sandy (October 2012). Sites with ocean exposure were more heavily eroded (Sandy Hook Oceanside, Breezy Point Oceanside, and Great Kills Oceanside), than sheltered sites (Sandy Hook Bayside, Breezy Point Bayside, Great Kills Bayside, Miller Field, Fort Wadsworth). The Sandy Hook and Great Kills Oceanside shorelines never fully recovered from the landward displacement caused by Hurricane Sandy and the shorelines continued to be displaced landward in the post-storm period. Persistent erosion post-storm also occurred in the coastal topography profiles along the bayside of Sandy Hook and Breezy Point. Beach nourishment efforts updrift affected post-storm recovery at Sandy Hook, Plumb Beach and Breezy Point by adding sediment into the system. Breezy Point Oceanside was the only site with a positive trend in shoreline and beach cross-section area gain over the report period. Erosion downdrift of structures at Plumb Beach and Great Kills Oceanside potentially threaten infrastructure located inland. Throughout the survey period there was consistent landward displacement of the shoreline and cross-section area loss downdrift of the eastern groin at Plumb Beach and of the bluff area at Great Kills. Consistent monitoring provides information for management, and trend analysis can help management anticipate and adjust to potential impacts.

In a comparison of shoreline change in this Trend Report with rates from the previous Trend Report, all shorelines within GATE except for Breezy Point Oceanside and Great Kills oceanside were more

negative in this recent period. Due to Hurricane Sandy and lack of recovery post-storm, Sandy Hook, Breezy Point Bayside, Plumb Beach, Great Kills Oceanside, Miller Field and Fort Wadsworth all had greater rates of landward shoreline displacement than during the previous period. Breezy Point Oceanside had a more positive shoreline displacement rate from 2012 to 2017 due to the large beach nourishment project in 2014. Great Kills Bayside had a similar seaward displacement rate in both trend reporting periods.

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Introduction

This 2012 to 2017 Trend Report incorporates both shoreline (1D) and coastal topographical (2D) change data at Gateway National Recreation Area (GATE), an earlier Trend Report incorporated only shoreline change data from Spring 2007 to Spring 2012 (Psuty et al. 2016e). This report follows the protocols described in the Northeast Coastal and Barrier Network Geomorphological Monitoring Protocol for ocean shoreline position (Psuty et al. 2010b) and coastal topography (Psuty et al. 2012). The shoreline position protocol was applied consistently in much of GATE for the first time in Spring 2006, and the coastal topography protocol was applied in Spring 2008. Subsequent surveys were conducted semi-annually throughout GATE through Spring 2017, and successive annual reports followed summarizing both shoreline and coastal topography datasets (Psuty et al. 2015b; Psuty et al. 2016a; Psuty et al. 2016b; Psuty et al. 2016d; Psuty et al. 2017b).

As prescribed in Standard Operating Procedure (SOP) #7 of both monitoring protocols (Psuty et al. 2010b, Psuty et al. 2012), the goal of the Trend Report is a summary of the database of shoreline positions and/or coastal topography data accumulated over the previous five years. It is a compilation of annual analyses that synthesize and characterize the data and interpret trends revealed by the numerical analyses. These longer-term comparisons of shoreline position and coastal topography changes reveal trends created by variation in sediment availability and in the intensity of formational processes. It is a comprehensive compilation of analyses that synthesize the geomorphology change data and provide aspects of scientific interpretation of the trends revealed in the numerical analyses.

Within this report, sites are grouped into three units (Figure 1):

- Sandy Hook Unit
- Jamaica Bay Unit: Breezy Point, Plumb Beach
- Staten Island Unit: Great Kills, Miller Field, Fort Wadsworth



Figure 1. Location and extent of the monitored shoreline positions and direction of alongshore transport at Gateway National Recreation Area Units.

Site and Situation

The portion of GATE covered in this report is composed of two coastal areas directly exposed to ocean processes (Sandy Hook and Breezy Point), and six other areas shielded to various degrees from the direct exposure to ocean conditions (Breezy Point Bay, Great Kills, Great Kills Bay, Miller Field, Fort Wadsworth, and Plumb Beach) (Figure 1). They each respond to the relative intensity of ocean energetics associated with their position and to the available sediment supply at their location, as described in Psuty et al. (2010a).

The primary geomorphological components of the GATE ocean-facing sites are the Sandy Hook barrier spit and Breezy Point/Jacob Riis Park component of the Rockaway barrier island that extend towards and into New York Harbor (Psuty et al. 2010a) (Figure 1). GATE also incorporates several ocean-facing sites on Staten Island, and an ocean-facing site at Plumb Beach. In addition, sites along the inlet margins and bay sides of the barriers have been incorporated into the monitoring effort. The segmentation of the shoreline, variable sediment input, and the wide range of exposure to the ambient wave and current conditions create differential responses to individual climatic events and to the net conditions at the shoreline and coastal topography. More information on the geomorphology of GATE is described in Psuty et al. 2010a, Psuty et al. 2017a, and Psuty et al. 2017b.

Natural and Anthropogenic Impacts on Shoreline Position and Coastal Topography

Storms are important drivers of coastal change at the ocean beach. Shoreline position and coastal topography are affected during storm events by the high-energy mobilization and transportation of beach and dune sediment. Generally, the winter season is considered a time of increased storminess characterized by higher energy levels and considerable sediment transport. The summer season is conversely characterized by lower energy levels and more opportunity for sediment retention. Shoreline position and coastal topography surveys are scheduled at six-month intervals to provide insight into the comparison between the conditions at the ends of the winter and summer seasons (though not to identify the effects of any specific storm). The seasonal signal, however, is often complicated by additional variables affecting ocean shorelines and topography. Structures at inlets and along the shoreline lead to localized sites of accumulation and loss; human activities manipulate sediment availability and pathways; inshore circulation cells create local erosion and sediment sequestering; alongshore transport can include pulses of sediment; etc.

Natural Impacts

To characterize the annual and 5-year sediment balances at a given site, metrics are to be generated of net shoreline and topographical change after seasonal stormy and non-stormy conditions. Storms are important drivers of the shoreline and topographical change and the protocols are attempting to monitor the results of stormy and non-stormy periods as net conditions, or seasonal contrasts. A measure of storminess is garnered by the water level data collected at the Sandy Hook, New Jersey tide gauge (Figure 2 and Table 1).

The value of 2.0 m (6.565 ft) above mean lower low water (MLLW) was selected for the threshold for defining a storm water elevation because it represents an elevation higher than the dry summer berm surface (a feature created by non-storm high tide levels) on the beach profiles that is exceeded during storms (Figure 3). The absolute value of the threshold is not diagnostic in itself, but it represents an elevation that is higher than the predicted lunar high tides. When it is reached, the upper beach and potentially the foredune undergo erosion and sediment redistribution, and overwash may occur. All of the daily water levels are illustrated with a solid vertical blue line that represents the maxima and minima of that date (Figure 2). Cyclonic storms (nor'easters and hurricanes) tend to be represented by several days of high water levels and frequently have a combination of very high waters during the periods that the winds are onshore followed by very low water levels during the succeeding periods when the winds are offshore. The water level data describe the seasonality of frequent storm events; storms occur more frequently during the winter and spring than in the summer (Figure 2 and Table 1). The maximum water level was measured during Hurricane Sandy (4.280 m) in October 2012 and there were six other storm events of great duration with high water exceeding the storm threshold for seven successive high tides (Table 1). The fall of 2012, winter of 2013, fall of 2015, and winter of 2016 seasons had notably high frequencies of stormy conditions.

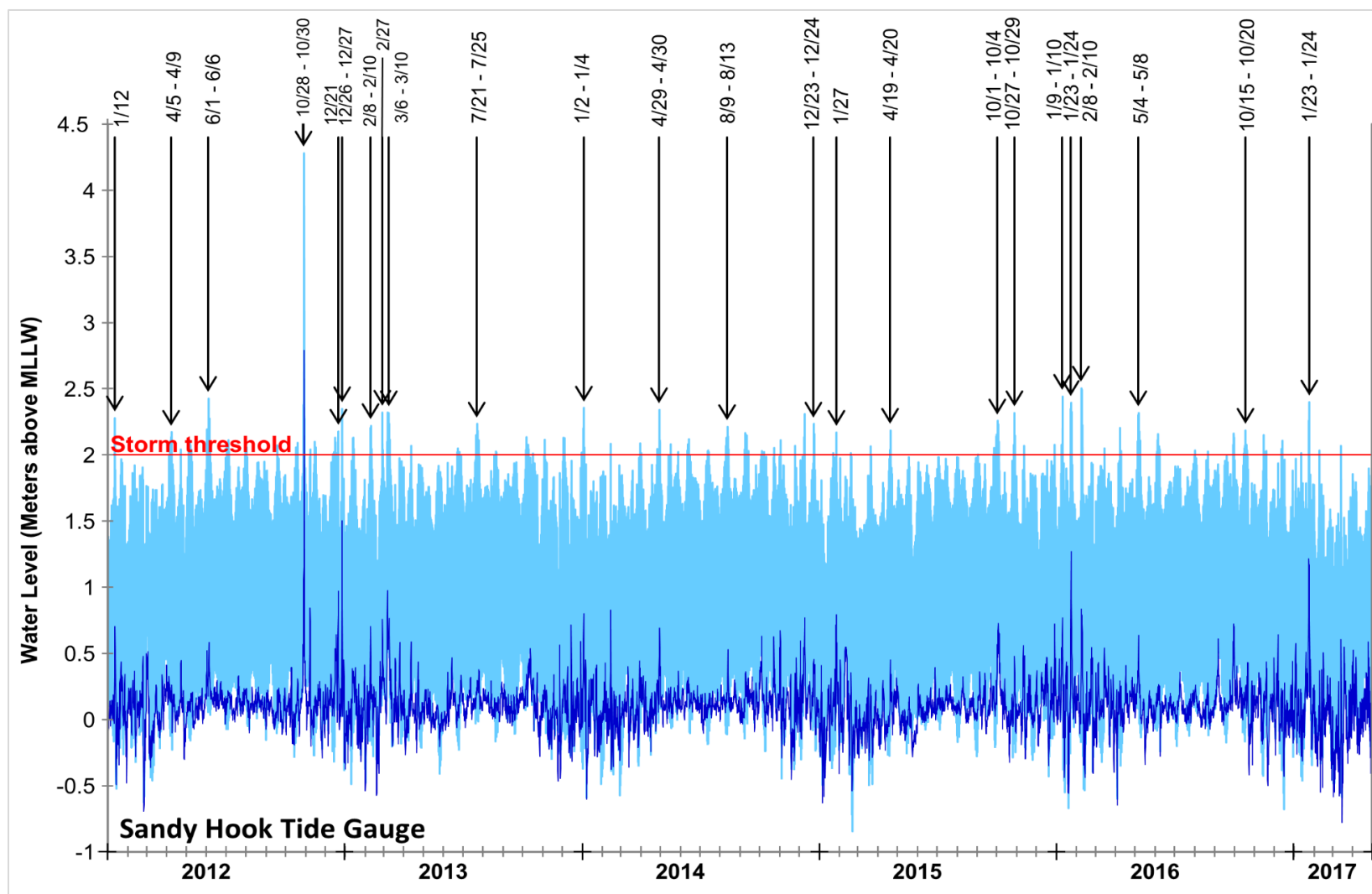


Figure 2. Daily water level variation at Sandy Hook, New Jersey Tide Gauge, with storm water levels surpassing the threshold value of 2.0 m above Mean Lower Low Water (MLLW). Dates of 25 maximum water levels during storm events are noted. Dark blue elevations represent surge values (difference of actual water level relative to predicted) Source: NOAA tide gauge (#8531680) Sandy Hook, NJ (<http://tidesandcurrents.noaa.gov/>).

Table 1. Frequency and magnitude of 25 highest water levels, 2012-2017, Sandy Hook, New Jersey tide gauge.

Storm	Number of high tides greater than 2.0 m (Storm threshold)	Maximum Water Level*		
		Tide height (m)	Date	Measured surge (m)
January 12, 2012	1	2.277	01/12/2012	0.704
April 5 - 9, 2012	4	2.172	04/08/2012	0.260
June 1 - 6, 2012	7	2.427	06/04/2012	0.436
October 28 - 30, 2012	5	4.280	10/29/2012	2.790
December 21, 2012	1	2.176	12/21/2012	0.802
December 26 - 27, 2012	2	2.348	12/27/2012	0.829
February 8 - 10, 2013	3	2.222	02/09/2013	0.454
February 27, 2013	2	2.321	02/27/2013	0.756
March 6 - 10, 2013	7	2.316	03/09/2013	0.664
July 21 - 25, 2013	7	2.234	07/22/2013	0.257
January 2 - 4, 2014	4	2.354	01/03/2014	0.505
April 29 - 30, 2014	4	2.34	04/29/2014	0.518
August 9 - 13, 2014	7	2.211	08/12/2014	0.294
December 23 - 24, 2014	2	2.234	12/23/2014	0.455
January 27, 2015	1	2.171	01/27/2015	0.670
April 19 - 20, 2015	3	2.185	04/20/2015	0.322
October 1 - 4, 2015	7	2.257	10/02/2015	0.471
October 27 - 29, 2015	4	2.317	10/28/2015	0.340
January 9 - 10, 2016	2	2.441	01/10/2016	0.770
January 23 - 24, 2016	3	2.396	01/23/2016	0.945
February 8 - 10, 2016	5	2.503	02/08/2016	0.784
April 7 - 9, 2016	2	2.204	04/07/2016	0.292
May 4 - 8, 2016	7	2.319	05/06/2016	0.336
October 15 - 20, 2016	6	2.186	10/18/2016	0.244
January 23 - 24, 2017	2	2.399	01/24/2017	1.169

* Water levels referenced to Mean Lower Low Water (MLLW)

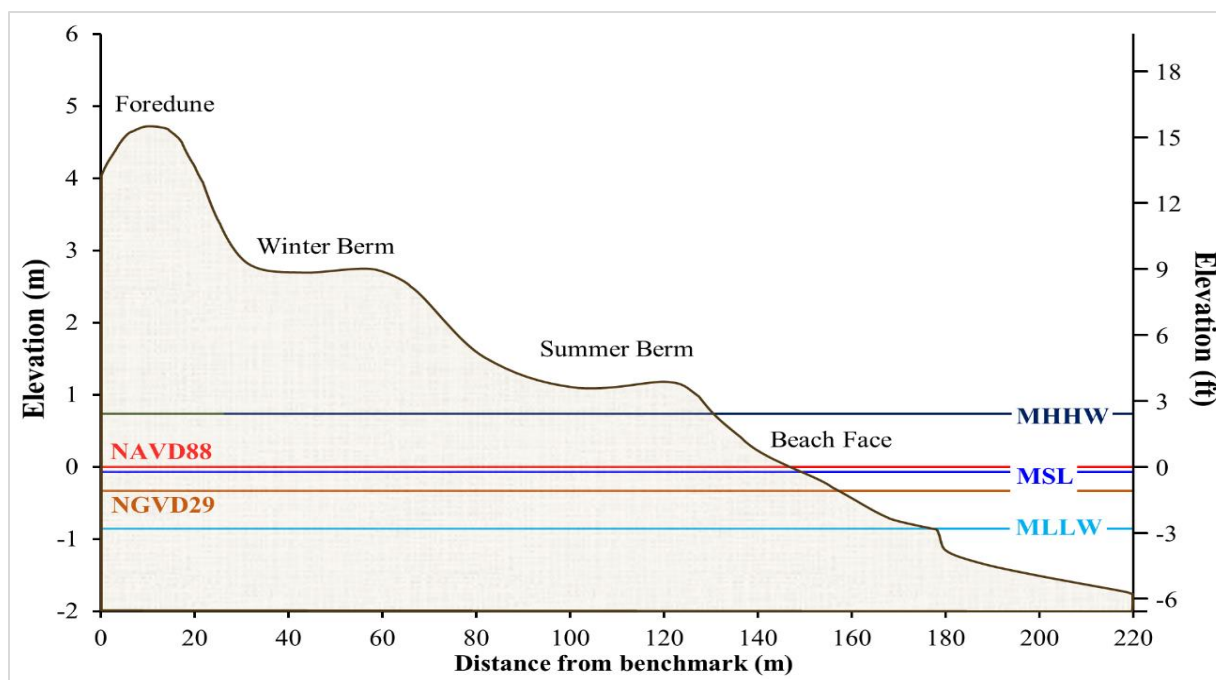


Figure 3. Relationship of 1983-2001 tidal epoch water levels to the North American Vertical Datum of 1988, to the 1929 National Geodetic Vertical Datum, and to a representative beach profile at Sandy Hook. All values are portrayed relative to NAVD88. Other terms are: MLLW = mean lower low water; NGVD29 = National Geodetic Vertical Datum of 1929; MSL = mean sea level; and MHHW = mean higher high water.

Anthropogenic Impacts

During the period of data collection for this Trend Report, eight beach nourishment events and four dredging events took place (Table 2). There were no nourishment events within the Sandy Hook Unit, however a total of 6,500,000 yds³ (4,970,000 m³) of sediment was placed updrift of Sandy Hook at Long Branch (United States Army Corps of Engineers [USACE] 2013c), Monmouth Beach (Cervenka 2015; USACE 2011a, 2013b), and Sea Bright beaches (Cervenka 2015; USACE 2013b) between November 2012 and March 2014 (Table 2). There were multiple anthropogenically-driven events that took place within Jamaica Bay Unit, including the placement of 127,000 yds³ (97,000 m³) at Plumb Beach (USACE 2013a) that was completed in October 2012, just before Hurricane Sandy. Along with the nourishment, a geotube groin was constructed along the eastern margin of the fill to serve as a temporary boundary to the emplaced fill. Shortly thereafter, in 2013, two permanent stone groins were constructed at the eastern and western margins of the fill at Plumb Beach, as well as a stone breakwater offshore of the fill. Nearby, affecting Breezy Point, about 200,000 yds³ (153,000 m³) of sediment was placed at Jacob Riis Park from February 2014 to July 2014 (Foderaro 2014; USACE 2014). Multiple nourishment projects were also completed updrift of Jacob Riis Park at Rockaway Beach in Fall 2012 (USACE 2011b, 2016), June 2013 to December 2013 (USACE 2014), and February 2014 to July 2014 (Foderaro 2014; USACE 2014), totaling about 3,772,000 yds³ (2,884,000 m³). There were no beach nourishment events within the Staten Island Unit. However, post-Hurricane Sandy, city parks along the adjacent non-NPS shoreline of Staten Island constructed an artificial dune as an emergency protective measure (NYC Special Initiative for Rebuilding and

Resiliency 2013). During this installation earth haulers moved sediment onto the beaches driving through Miller Field. This process disturbed some topography and left tire tracks in the beach and park maintenance worked with front end loaders to restore the disturbed section of the beach (Frame 2018, Ringenary 2018). The sediment piled by park maintenance remained in place at Miller Field and was vegetated over time. At Great Kills, 300 m - 500 m northeast of the Bath House, storm-displaced overwash sediment was removed from the road and nearby parking lot and was used to construct a berm adjacent to a post-Hurricane Sandy overwash area (Frame 2018).

Four dredging events occurred over the 5-year survey period. Dredging at Great Kills from January 2014 to March 2014 removed 237,000 yds³ (181,000 m³) of sediment (Table 2) from a portion of an accreting node at the southwestern end of the site (USACE 2013d). Three dredging events occurred in the Sandy Hook Navigation Channel in Winter 2012 (USACE 2013e), from November 2013 to December 2013 (USACE 2013e, 2015), and the Winter of 2015 (USACE 2015), totaling 687,000 yds³ (525,000 m³) of sediment removed. The sediment dredged from the Sandy Hook Navigation Channel was placed at an offshore Historic Area Remediation Site (HARS).

Table 2. Beach nourishment and dredging projects at or updrift of Gateway National Recreation Area beaches, Spring 2012 – Spring 2017.

Location	Sediment Placed or Dredged		Time Period
	Cubic Yards	Cubic Meters	
Sandy Hook Navigation Channel Dredging	-176,000	-135,000	Winter 2012
Plumb Beach	127,000	97,000	Completed Oct. 2012
updrift of Jacob Riis Park, Rockaway Beach	272,000	208,000	Oct. - Nov. 2012
updrift of Sandy Hook, Monmouth Beach	800,000	612,000	Nov. 2012
updrift of Sandy Hook, Sea Bright / Monmouth Beach	2,200,000	1,682,000	Jul. - Nov. 2013
updrift of Sandy Hook, Long Branch Beach	3,500,000	2,676,000	Nov. 2013 - Mar. 2014
Sandy Hook Navigation Channel Dredging	-261,000	-200,000	Sep. - Dec. 2013
updrift of Jacob Riis Park, Rockaway Beach	600,000	460,000	June - Dec. 2013
Great Kills Harbor Channel Dredging	-237,000	-192,000	Jan. - Mar. 2014
updrift of Jacob Riis Park, Rockaway Beach	2,700,000	2,064,000	Feb. - Jul 2014
Jacob Riis Park Beach	200,000	153,000	Feb. - Jul 2014
Sandy Hook Navigation Channel Dredging	-250,000	-191,000	Winter 2015

Shoreline Position Surveys (1D)

Timing of Shoreline Position Surveys

Shoreline position is collected at GATE semi-annually and the seasonal variation is examined in annual reports. For this Trend Report, only the six spring shorelines from 2012 – 2017 (Table 3) are compared at each site to elucidate trends and patterns in shoreline position change. The high-tide shoreline positions compared in this report were all collected during the predicted neap-tide period to ensure that water level elevations were similar.

According to protocol (Psuty et al. 2010b), water level elevations should be determined prior to survey by utilizing the nearest NOAA tide gauge to verify non-storm conditions. The nearest gauge that portrays the ocean condition is at the northern end of Sandy Hook, NOAA National Ocean Data Center, Station #8531680 (<http://tidesonline.nos.noaa.gov/>). This gauge was used to reference water level positions and the timing of high water levels in this report.

Table 3. Spring shoreline surveys and recorded elevations of previous neap tide high-tides at Gateway National Recreation Area.

Season	Park	Date of survey	Previous High Tide	
			Height* (m)	Time
Spring 2012	Sandy Hook	03/30/2012	1.295	1:12 PM
	Breezy Point	03/29/2012	1.343	12:21 PM
	Plumb Beach	03/27/2012	1.340	10:48 AM
	Great Kills	03/29/2012	1.174	12:12 PM
	Miller Field	03/30/2012	1.295	1:12 PM
	Fort Wadsworth	03/30/2012	1.295	1:12 PM
Spring 2013	Sandy Hook	04/19/2013	1.277	2:34 PM
	Breezy Point	04/16/2013	1.318	12:02 PM
	Plumb Beach	03/21/2013	1.207	3:14 PM
	Great Kills	03/18/2013	1.262	12:33 PM
	Miller Field	03/20/2013	1.199	2:17 PM
	Fort Wadsworth	03/20/2013	1.199	2:17 PM
Spring 2014	Sandy Hook	05/09/2014	1.538	3:45 PM
	Breezy Point	05/11/2014	1.368	4:47 AM
	Plumb Beach	03/11/2014	1.534	3:39 AM
	Great Kills	03/10/2014	1.237	3:19 PM
	Miller Field	03/10/2014	1.237	3:19 PM
	Fort Wadsworth	03/10/2014	1.237	3:19 PM

*Water levels are referenced to Mean Lower Low Water (MLLW) Source: NOAA tide gauge (#8531680) Sandy Hook, New Jersey.

Collection of Shoreline Position and Development of Metrics of Change

Shoreline collection and change analysis are completed according to the shoreline change monitoring protocol, as described in Psuty et al. (2010b). The Digital Shoreline Analysis System (DSAS) program (Thieler et al. 2009) and Shoreline Change Mapper, a software application that works within ESRI's ArcGIS software and was developed by Aaron Love of the Sandy Hook Cooperative Research Programs (see SOP # 7, Psuty et al. 2010b), are used to develop and portray metrics of shoreline change. The distribution and dimensions of shoreline change are depicted by a series of vectors that represent direction and magnitude of change between two shoreline position datasets in a manner similar to a bar graph (Figure 4), with the offshore baseline as an x-axis. Longer vectors represent greater magnitude of change, either in the positive (seaward) direction or in the negative (landward) direction at the location of any particular transect, whereas shorter vectors represent a lesser magnitude of change.

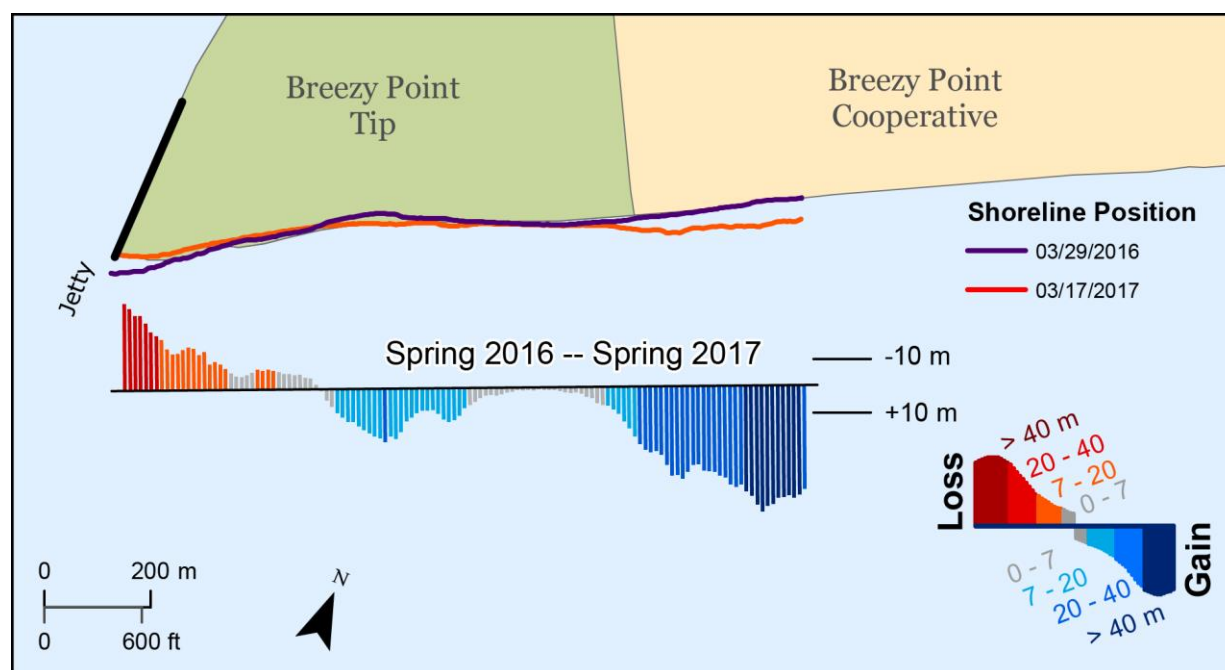


Figure 4. Sample of vectors of change produced by Shoreline Change Mapper to represent magnitude and direction of annual shoreline change for a sampling of transects at Breezy Point Oceanside, Gateway National Recreation Area, Spring 2016 – Spring 2017.

There is statistical uncertainty involved with shoreline change analysis. Specific sources of uncertainty are detailed in the shoreline monitoring protocol (Psuty et al. 2010b). For a comparison between two shorelines, there is uncertainty of ± 7 m for an exposed shoreline and ± 3 m for a sheltered shoreline. Vectors representing displacement at sheltered shorelines with values less than uncertainty (± 7 m or ± 3 m, respectively) are represented as gray. Seaward shoreline displacement values greater than the uncertainty (± 7 m exposed shoreline, ± 3 m sheltered shoreline) are represented by shades of blue and indicate accretion or gain. Landward shoreline displacement

values greater than the uncertainty are represented by shades of red and indicate erosion or loss (Figure 4).

For this 5-year Trend Report, annual changes in spring shoreline position, 5-year change from Spring 2012 – Spring 2017, and traces of selected surveyed shorelines are portrayed spatially for each GATE site (e.g., Figure 5). Further, the difference measurements between shoreline positions for all GATE sites are subjected to statistical analysis to determine the mean and standard deviation of annual and trend comparisons. The difference measurements for the 5-year comparisons are also represented by histograms of the frequency of individual magnitudes of change to identify modal characteristics of the dimensions of change.

Shoreline Position Metrics of Change

Sandy Hook Unit

Sandy Hook is a spit that extends into New York Harbor. Surveys using the shoreline change monitoring protocol (Psuty et al. 2010b) were conducted along the entire ocean-facing shoreline from the boundary with Sea Bright, and along the Inlet-Facing Segment that includes the inlet-facing shoreline and part of the bayside shoreline to the limit of the Coast Guard property (Figure). The dominant sediment transport direction is from south to north along the oceanside shoreline, from east to west along the inlet-facing shoreline, and from north to south along the bayside shoreline.

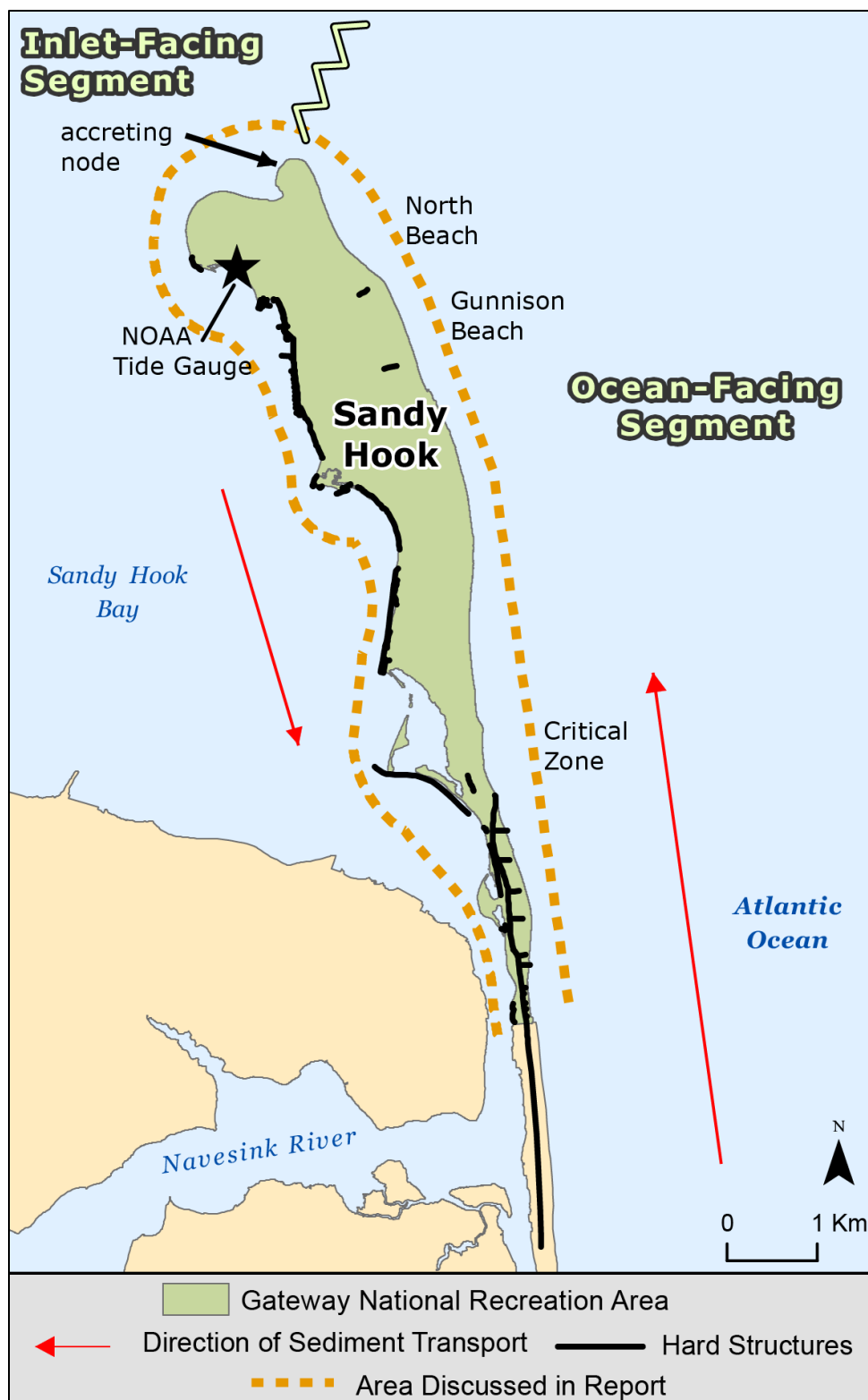


Figure 5. Features and descriptive characteristics of the Sandy Hook Unit, Gateway National Recreation Area survey site. The yellow zig-zag line divides the Inlet-Facing Segment from the Ocean-Facing Segment.

Annual Shoreline Change

The shoreline at Sandy Hook was affected by relative storminess (Figure 2), by updrift beach nourishment in Long Branch, Monmouth Beach, and Sea Bright (Figure 1 and Table 3), and by dredging of the Sandy Hook Navigation Channel. Dredging of the channel was completed very close to the accreting node of Sandy Hook and led to portions of the beach sloughing off into the channel, and effectively eroding the shoreline position. Portions of the beach were closed due to wildlife protection closures (threatened piping plover nesting area) during the time of the Spring 2013 shoreline survey and caused gaps in the shoreline collection.

In all annual survey comparisons (Figure 6), except Spring 2014 – Spring 2015, there was landward displacement along most of the shoreline south of Gunnison Beach, landward displacements ranged from about -1 m to -45 m. In the Spring 2014 – Spring 2015 comparison, there was seaward displacement from the southern park boundary to the northern margin of the ocean-facing shoreline (Figure 6). The amount of seaward displacement generally increased in magnitude from south to north, +1 m to +44.52 m, before tapering off northwest of North Beach. The variability in the displacements, especially at and south of Critical Zone, were due to both storminess and sediment availability, sediment was placed updrift of Sandy Hook in November 2012, Fall 2013, and Winter 2014.

The ocean-facing shoreline north of Gunnison Beach varied considerably over the 5 annual comparisons, from about -30 m of landward displacement to about +80 m of seaward displacement (Figure 6). The stormiest years (Spring 2012 – Spring 2013 and Spring 2015 – Spring 2016) had the greatest amount of landward displacement, ranging from about -10 m to -81 m at the northern margin of the ocean-facing shoreline. These two years of exceptional landward displacement were also years when dredging of the Sandy Hook Navigation Channel occurred, and that removal contributed to the landward displacement of the shoreline. However, despite Hurricane Sandy, the Spring 2012 – Spring 2013 annual comparison, a mean of -9.36 m, was typical relative to other annual comparisons (e.g., Spring 2015 – Spring 2016, a mean of -9.25 m) because the recovery from Hurricane Sandy occurred on a seasonal time scale. Along the northern tip of Sandy Hook, there was relatively moderate displacement throughout the annual comparisons that ranged from about -20 m to +11 m (Figure 6) due to reduced exposure to incident wave energy at the shoreline. The magnitude of seaward shoreline displacement increased near the accreting node and varied from +2 m to +60 m in the annual comparisons.

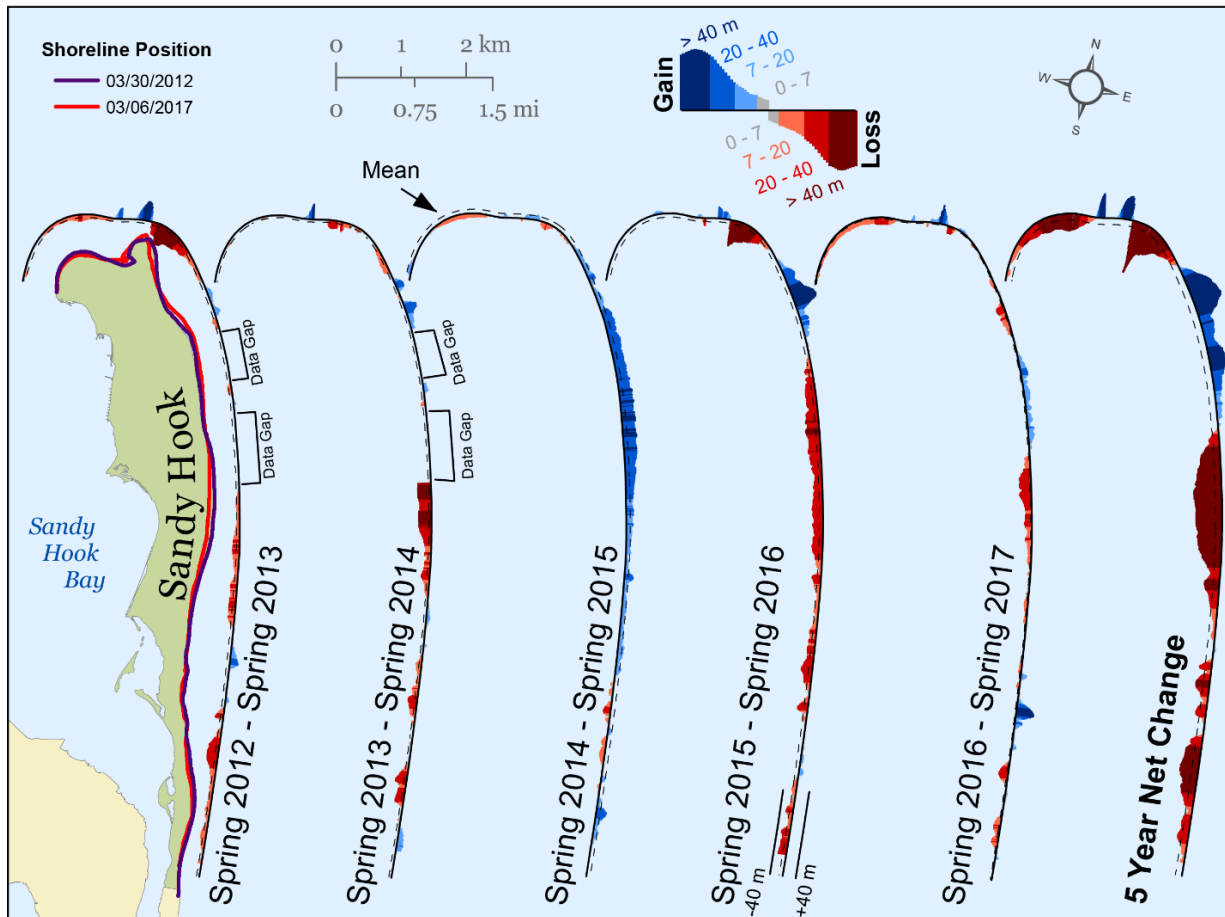


Figure 6. Distribution of annual and 5-year shoreline change at Sandy Hook Unit, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the Spring 2015 – Spring 2016 comparison. Data gaps in the Spring 2013 shoreline survey produced gaps in Spring 2012 – Spring 2013 and Spring 2013 – Spring 2014 shoreline comparisons.

5-Year Shoreline Change

Nearly the entire surveyed shoreline, except the shoreline just northwest of North Beach through Gunnison Beach and the inlet-facing shoreline of the accreting node of Sandy Hook, had landward displacement. The landward displacement on the ocean-facing shoreline generally increased from south to north, ranging from about -2 m to -88 m. Along the shoreline of the Inlet-Facing Segment, the landward displacement increased from west to east from about -4 m to -54 m (Figure 6). The shoreline just northwest of North Beach through Gunnison Beach gained sediment from areas of landward displacement updrift, with seaward displacements ranging from about +10 m to +92 m, increasing from south to north. The mean change of the Sandy Hook shoreline over the 5-year period was -25.85 m (Figure 6). This mean value integrated the variety of weather factors, updrift inputs of sediment from beach nourishment projects, dredging of the Sandy Hook Navigation Channel, and changes in orientation of the shoreline.

A histogram of the distribution of dimensions of change had a multimodal characteristic (Figure 7), suggesting areas of unique responses. The highest peak had a range of -20 m to -50 m, greater than

the ± 7 m uncertainty value, and represented the majority of vectors of change in the southern half of the Ocean-Facing Segment and the landward displacement that occurred along the Inlet-Facing Segment. A lesser peak ranging from -80 m to -90 m represented vectors of change along the northernmost portion and central portion of the ocean-facing shoreline. The maximum landward displacement of the shoreline, -163.03 m, occurred on the northern ocean-facing margin of the accreting node. A small peak from +70 m to +80 m represented the seaward displacement along the Inlet-Facing Segment and the northwest of North Beach where the maximum seaward displacement, +91.39 m, occurred.

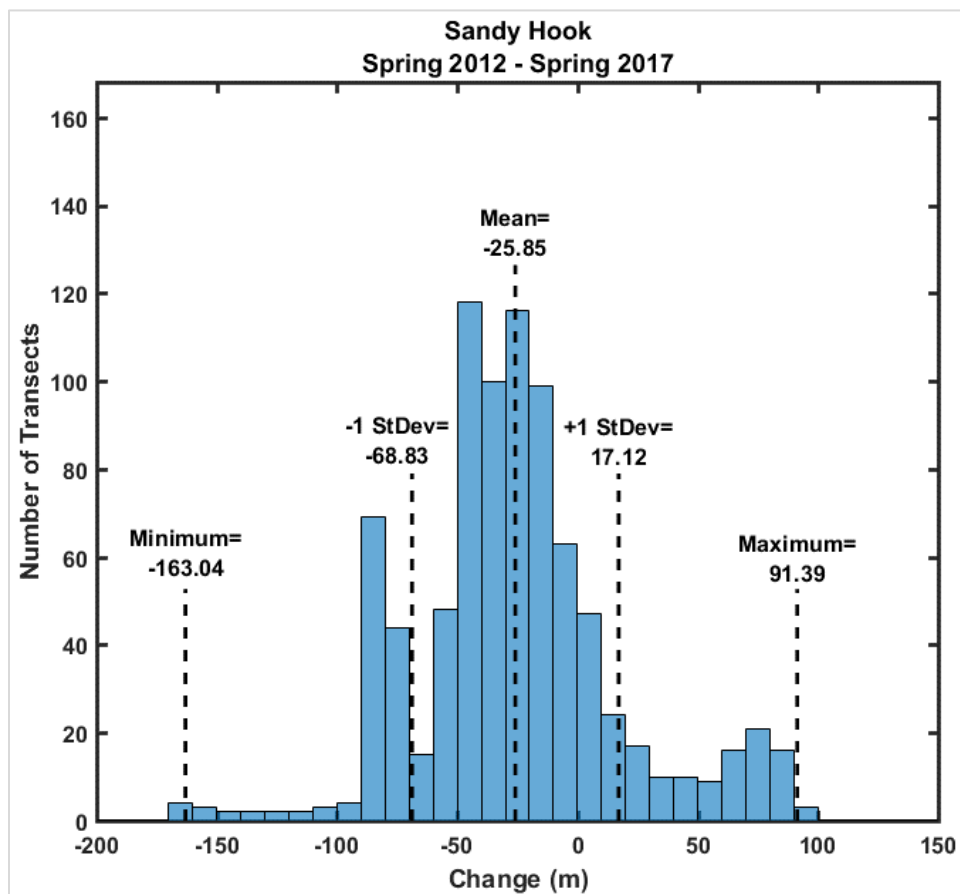


Figure 7. Histogram of vectors of shoreline change, 5-year trend from Spring 2012 to Spring 2017 at Sandy Hook Unit, Gateway National Recreation Area.

Summary Statistics Tables and Trends of Change

The Sandy Hook shoreline data are assembled to represent seasonal, annual, and 5-year metrics of shoreline change (Table 4). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics at Sandy Hook varied from -25.08 m of landward displacement (Spring 2012 – Fall 2012) to +15.72 m of seaward displacement (Fall 2012 – Spring 2013). There was mean seaward displacement in Spring 2014 – Spring 2015, +6.99 m, whereas there was mean landward displacement in all other annual

comparisons. The maximum mean landward displacement of -9.36 m occurred in Spring 2012 – Spring 2013 (Table 4).

Table 4. Seasonal, annual, and 5-year metrics of shoreline change for Sandy Hook Unit, Gateway National Recreation Area, 2012 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012**	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012	-25.08	-25.08	23.22	42.28	-64.48
	Fall 2012 - Spring 2013*	15.72	-9.36	21.96	58.36	-32.56
	Spring 2013 - Fall 2013*	2.59	-6.77	7.80	29.50	-15.35
	Fall 2013 - Spring 2014	-11.83	-18.60	13.97	57.05	-41.46
	Spring 2014 - Fall 2014	7.02	-11.57	10.77	28.34	-20.22
	Fall 2014 - Spring 2015	-0.03	-11.60	7.28	28.69	-14.50
	Spring 2015 - Fall 2015	1.36	-10.24	15.19	64.07	-47.56
	Fall 2015 - Spring 2016	-10.61	-20.85	14.91	26.30	-46.15
	Spring 2016 - Fall 2016	-10.94	-31.79	11.49	32.64	-47.24
	Fall 2016 - Spring 2017	5.94	-25.85	11.89	75.81	-24.61
Annual	Spring 2012 - Spring 2013*	-9.36	-9.36	15.61	60.06	-65.26
	Spring 2013 - Spring 2014*	-9.24	-18.60	15.77	48.53	-42.75
	Spring 2014 - Spring 2015	6.99	-11.60	12.77	44.52	-23.44
	Spring 2015 - Spring 2016	-9.25	-20.85	22.19	72.90	-81.81
	Spring 2016 - Spring 2017	-5.00	-25.85	14.15	58.69	-37.54
Net	Spring 2012 - Spring 2017	-25.85	-25.85	42.97	91.39	-163.04

* indicates that there is a gap in the shoreline data during the specified time period, only transects without data gaps were used in the calculation of statistics.

** transects with missing data were not used to calculate this statistical value because missing data reduces the comparability to the 2012 shoreline.

The net shoreline displacement starting with the Spring 2012 survey was calculated for each successive seasonal, annual, and 5-year temporal span. Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement. However, the calculation requires comparable data sets with no gaps in shoreline position data. To apply net mean displacement analysis to the shoreline of Sandy Hook, only vectors of change that were present in every shoreline comparison were incorporated in the analysis.

Trends of the changes, expressed as a general rate of change per year, albeit not a predictive value, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Spring 2006 to the Spring 2017 survey (Figure 8). To best understand the effects of shoreline displacement and recovery on the overall linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provided greater detail. This analysis indicates that the mean

shoreline position at Sandy Hook was displaced landward at the rate of -0.90 m/yr from Spring 2006 to Spring 2017 (Figure 8). For many seasons there was increased difference between the net displacement points and the linear regression line, a function of updrift beach nourishment and major storm events (Hurricane Sandy) affecting the natural trend of the shoreline displacement. The rate of shoreline displacement had changed from $+0.65$ m/yr from Spring 2006 to Spring 2012 to -3.54 m/yr from Spring 2012 to Spring 2017. Perhaps the increase in displacement rate was due to the erosion caused by Hurricane Sandy.

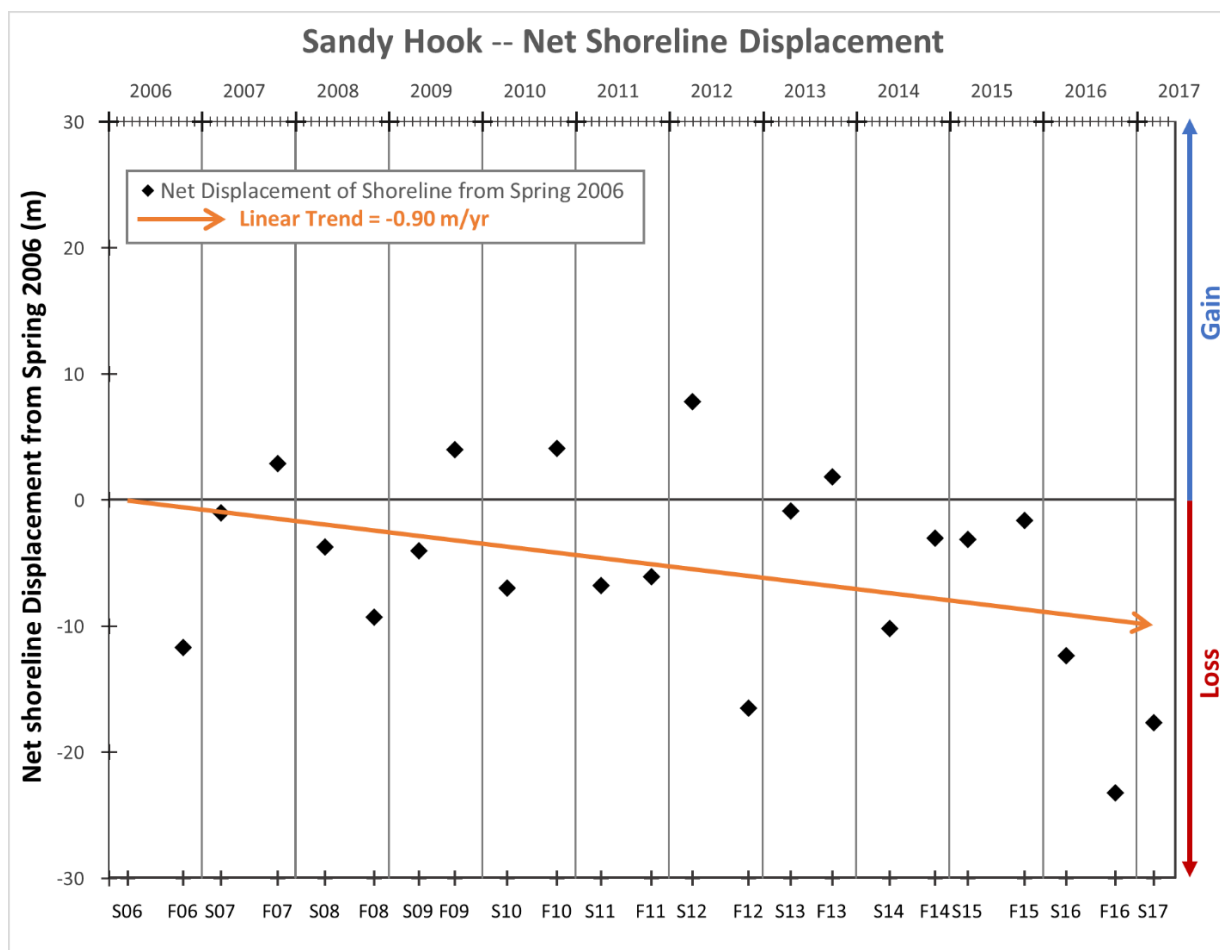


Figure 8. Trend of mean seasonal shoreline net displacement at Sandy Hook Unit, Gateway National Recreation Area Spring, 2006 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Jamaica Bay Unit

Breezy Point

Breezy Point is a portion of the Rockaway barrier island that extends westerly into New York Harbor. The Breezy Point shoreline is composed of two portions: 1) the ocean-facing portion with an exposure to the Atlantic Ocean to the south; and 2) the portion toward the west and bayside (figure 9). The two portions are separated by a jetty that is located at the western terminus of the barrier

island and limits alongshore transport of sediment. The direction of sediment transport along the oceanside shoreline is toward the southwest. On the bayside, the direction of sediment transport is toward the northeast. Breezy Point Bayside is a sheltered site and is exposed to much less incident wave energy than the oceanside portion.

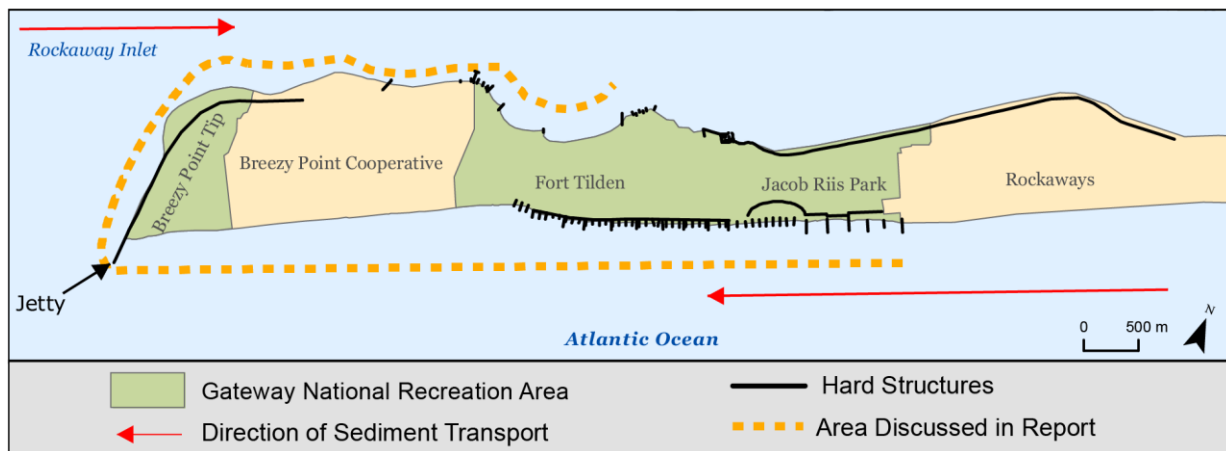


Figure 9. Features and descriptive characteristics of the Breezy Point surveys site, Jamaica Bay Unit, Gateway National Recreation Area.

Breezy Point Oceanside

Annual Shoreline Change

The oceanside shoreline at Breezy Point was affected by the variety of engineering structures updrift of the park that limited the input of sediment at the eastern margin (Figure 9), by relative storminess (Figure 2), and by the input of new sediment at Riis Park and from updrift beach nourishment (Table 2). The Spring 2012 – Spring 2013 comparison had landward displacement along the entire ocean-facing shoreline at Breezy Point, due to the occurrence of Hurricane Sandy. From Spring 2012 to Spring 2013, there was a mean displacement of -20.38 m landward. During this period, the vectors in the western portion had a mean displacement of -27.71 m and the eastern portion had a mean landward displacement of -12.02 m (Figure 10). A nourishment episode occurred updrift of Jacob Riis Park October-November 2012 that aided in the post-storm recovery as sediment was transported downdrift into the eastern portion of the shoreline.

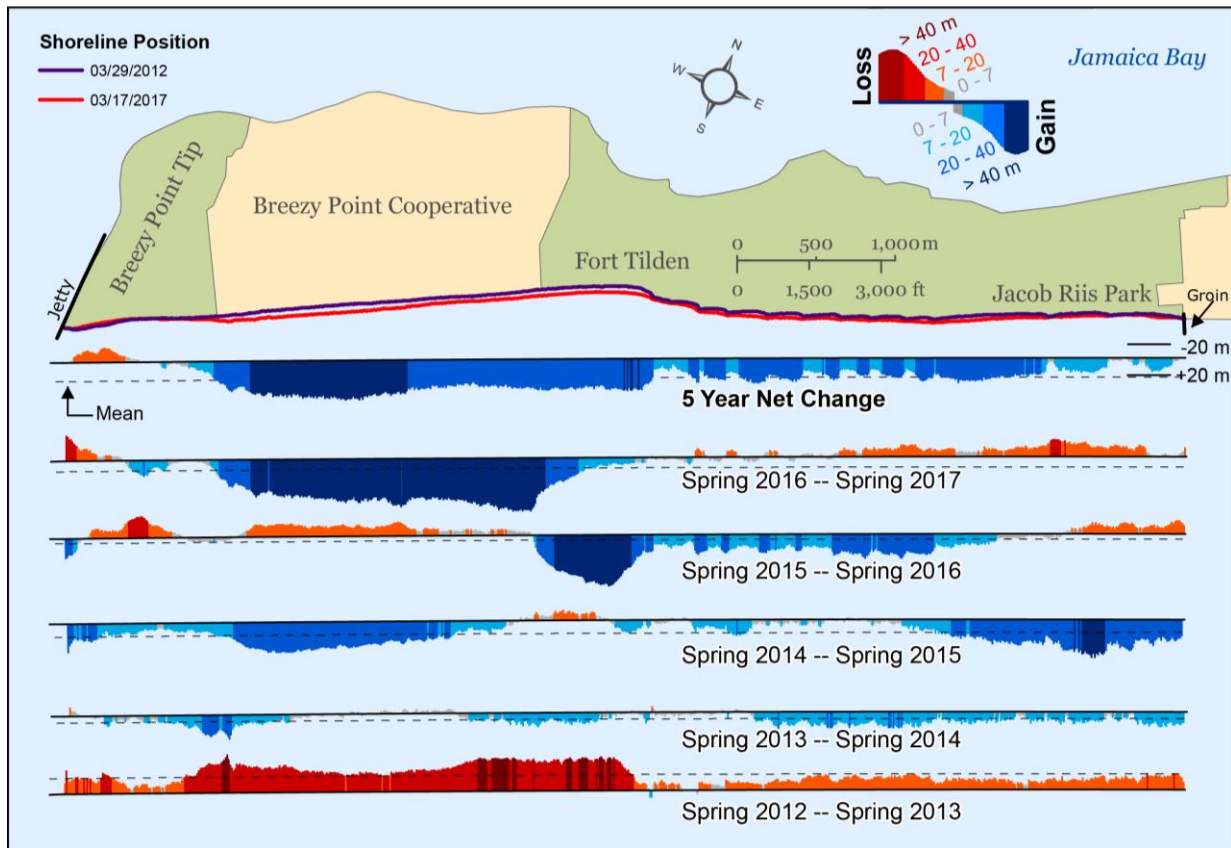


Figure 10. Distribution of annual and 5-year shoreline change at Breezy Point Oceanside, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the 5-year net change comparison.

In each annual comparison from the Spring 2014 – Spring 2015 comparison to the Spring 2016 – Spring 2017 comparison, there were areas of seaward displacement that shifted westward. The shifting areas of displacement were related to the nourishment event that occurred at and updrift of Jacob Riis Park June-December 2013 and February-July 2014. From the Spring 2015 – Spring 2016 comparison to the Spring 2016 – Spring 2017 comparison, the extent of landward displacement in the eastern portion of the shoreline extended farther westward (Figure 10). There were no new nourishment events after July 2014 and the large terminal groin at the eastern border of Jacob Riis Park effectively retained sediment at the beach face updrift and also directed sediment transport offshore limiting any accumulation on the beach.

5-Year Shoreline Change

The entire shoreline, except near the jetty, had seaward displacement, increasing from east to west (Figure 10). The Breezy Point ocean shoreline recovered from Hurricane Sandy except in the westernmost portion of Breezy Point Tip over the 5-year net period (Figure 10). The mean change over the 5-year period was +24.21 m. The western portion had greater recovery, a mean of about +29 m compared to a mean of +19 m in the eastern portion. The shoreline near the jetty at Breezy Point Tip eroded over the 5-year period and had landward displacements ranging from -10 m to -20 m (Figure 10). A histogram of the distribution of dimensions of change was negatively skewed with a

multimodal characteristic (Figure 11). The greatest peak, from +35 m to +40 m, greater than the ± 7 m uncertainty value, occurred at the Breezy Point Cooperative shoreline with help from sediment recovery low on the post-Hurricane Sandy beach profile, as well as sediment placed updrift at Riis Park. The lesser peak in the distribution had a range of +20 m to +25 m and represented the shoreline position at Fort Tilden and Jacob Riis Park.

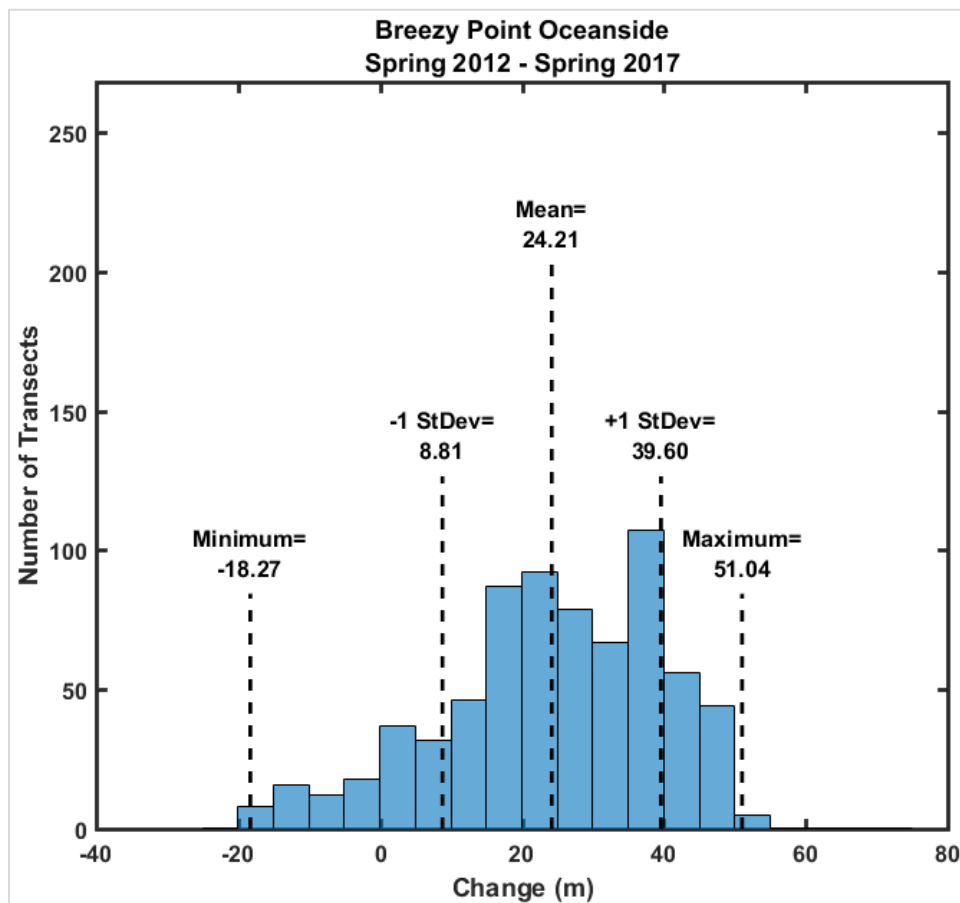


Figure 11. Histogram of vectors of shoreline change, from Spring 2012 to Spring 2017 at Breezy Point Oceanside, Gateway National Recreation Area.

Summary Statistics Tables and Trends of Change

The Breezy Point Oceanside data are assembled to represent seasonal, annual, and 5-year metrics of shoreline change (Table 5). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics varied from -14.42 m of landward displacement (Fall 2012 – Spring 2013) to +15.19 m of seaward displacement (Spring 2014 – Fall 2014). There was a mean landward displacement of -20.38 m, in the first annual comparison (Spring 2012 – Spring 2013) and there was mean seaward displacement in all other annual comparisons, with a maximum mean seaward displacement of +16.56 m that occurred Spring 2014 – Spring 2015 (Table 5).

Table 5. Seasonal, annual, and 5-year metrics of shoreline change for Breezy Point Oceanside, Gateway National Recreation Area, 2012 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012	-5.97	-5.97	5.53	10.94	-24.36
	Fall 2012 - Spring 2013	-14.42	-20.38	11.51	26.86	-45.13
	Spring 2013 - Fall 2013	14.97	-5.42	10.19	45.37	-17.62
	Fall 2013 - Spring 2014	-6.48	-11.89	12.67	31.01	-56.31
	Spring 2014 - Fall 2014	15.19	3.30	16.53	70.09	-13.96
	Fall 2014 - Spring 2015	1.37	4.67	12.99	30.15	-35.68
	Spring 2015 - Fall 2015	5.38	10.05	7.78	25.74	-11.73
	Fall 2015 - Spring 2016	0.90	10.95	18.71	67.50	-40.41
	Spring 2016 - Fall 2016	6.42	17.37	24.83	64.72	-50.17
	Fall 2016 - Spring 2017	6.83	24.21	7.83	25.80	-13.61
Annual	Spring 2012 - Spring 2013	-20.38	-20.38	11.20	9.38	-48.73
	Spring 2013 - Spring 2014	8.49	-11.89	7.01	31.26	-10.94
	Spring 2014 - Spring 2015	16.56	4.67	13.49	49.25	-13.50
	Spring 2015 - Spring 2016	6.28	10.95	19.58	65.23	-27.67
	Spring 2016 - Spring 2017	13.26	24.21	26.43	67.98	-28.02
Net	Spring 2012 - Spring 2017	24.21	24.21	15.39	51.04	-18.27

The net shoreline displacement starting with the Spring 2012 survey was also calculated for each successive seasonal, annual, and 5-year temporal span (Table 5). Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement.

Trends of the changes, expressed as a general rate of change per year, albeit not a predictive value, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Spring 2006 to the Spring 2017 survey (Figure 12). To best understand the effects of shoreline displacement and recovery on the overall linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provide greater detail. This analysis indicates that the mean shoreline position at Breezy Point Oceanside was displaced seaward at the rate of +3.79 m/yr from Spring 2006 to Spring 2017 (Figure 12). The trend line does not fit the Breezy Point mean shoreline net displacement data well, a function of beach nourishment and major storm events (Hurricane Sandy) affecting the natural trend of the shoreline displacement. There was beach nourishment in updrift communities in 2007, 2009, 2010, and nourishment both updrift and in Jacob Riis in 2014. From 2006 to 2012 the shoreline was displaced seaward at a rate of +1.61 m/yr, from 2012 – 2017 the shoreline was displaced seaward at a rate of +6.51 m/yr. This increase in seaward displacement is due to the large nourishment episode updrift in 2014 (Table 2).

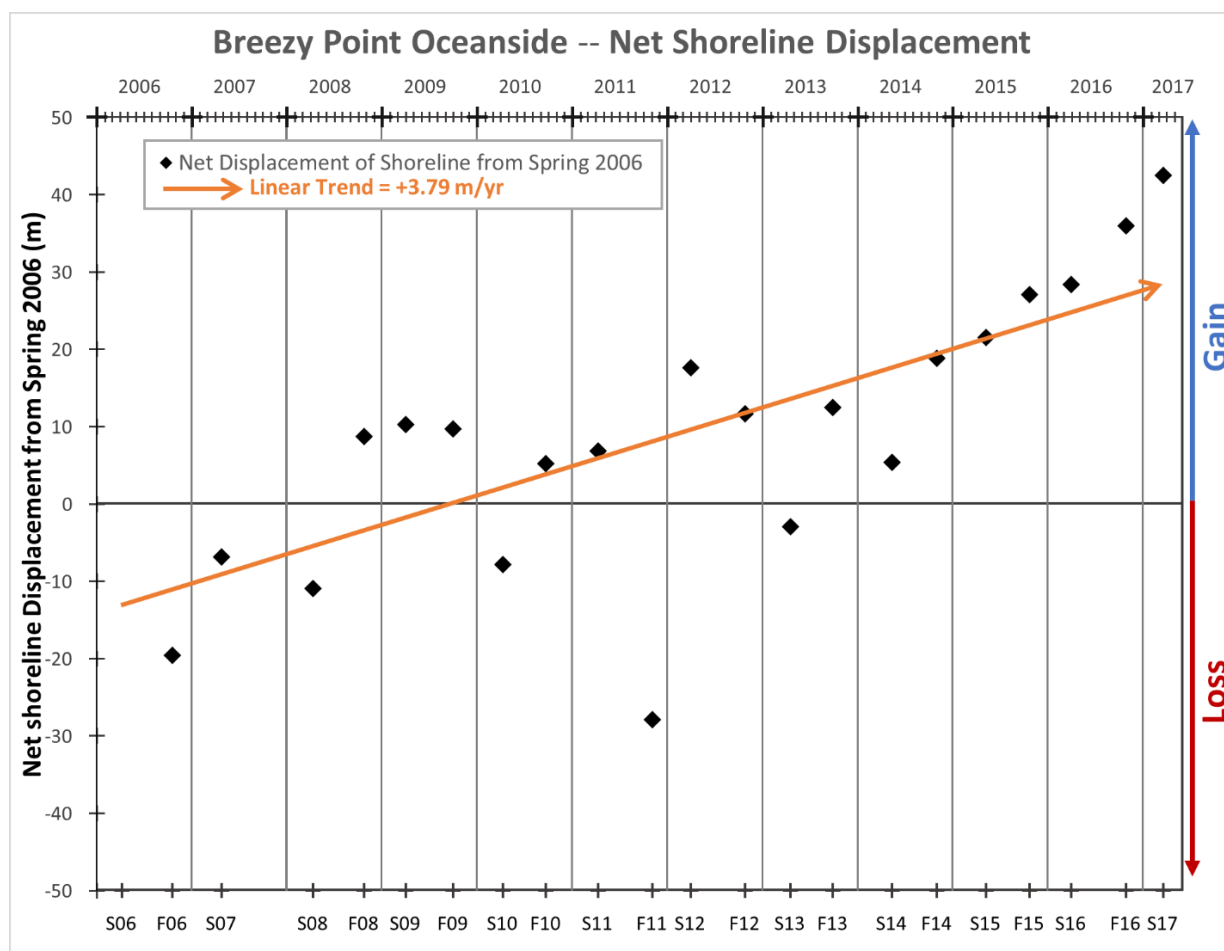


Figure 12. Trend of mean seasonal shoreline net displacement at Breezy Point Oceanside, Gateway National Recreation Area, Spring 2006 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Breezy Point Bayside

A large data gap occurred at Breezy Point Bayside in Spring 2012 that limited the time period of the net change comparison to four years (Spring 2013 – Spring 2017) and limited the Spring 2012 – Spring 2013 annual comparison to the western margin of Breezy Point.

Annual Shoreline Change

The bayside shoreline at Breezy Point was affected by relative storminess, mostly on the western facing portion. The two annual comparisons with the stormiest winter seasons (2012 – 2013 and 2015 – 2016) had large landward displacements of -15 m to -20 m near the inlet margin (Figure 13). Conversely, the comparison with the least stormy winter (2016 – 2017) had the greatest seaward displacement near the inlet margin, a maximum seaward displacement of +49 m (Figure 13). The western margin of Breezy Point Cooperative had consistent accumulation in every annual comparison except for 2015 – 2016. The shoreline at the western margin of Breezy Point Cooperative from Spring 2015 to Spring 2016 was displaced landward -10 m to -15 m due to increased storminess during the fall and winter seasons. For all the other annual comparisons, the

maximum annual seaward displacement was about +10 m from Spring 2012 to Spring 2013 and increased to +25 m of seaward displacement from Spring 2016 to Spring 2017 (Figure 13). To the east, where the shoreline was more sheltered, the majority of annual displacements were relatively modest and fluctuated within the realm of uncertainty of ± 3 m during the surveyed periods. Displacements during the survey period that did not fall within the uncertainty range, varied between ± 5 m and ± 10 m.

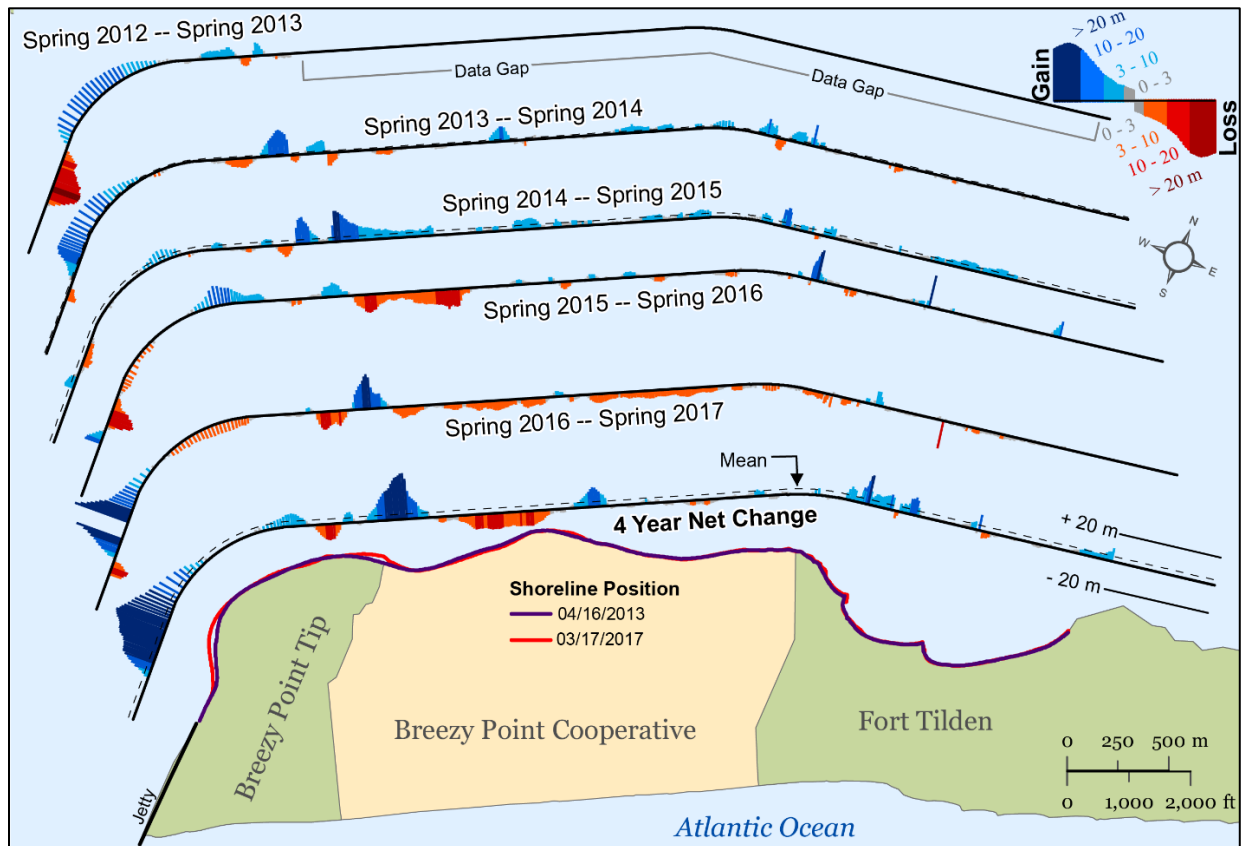


Figure 13. Distribution of annual and 4-year shoreline change at Breezy Point Bayside, Gateway National Recreation Area. The 4-year net change comparison is from Spring 2013 – Spring 2017. The scale for all vectors of change is incorporated on the 4-year net change comparison.

4-Year Shoreline Change

The inlet margin recovered from the stormy periods of 2012-2013 and 2015-2016 over the 4-year net period (Figure 13). The inlet margin had an average net seaward displacement of +20 m including a maximum seaward displacement of +37.85 m. The shoreline at the western margin of Breezy Point Cooperative had net seaward displacement over the 4-year period with a maximum seaward displacement of +32.39 m. Downdrift (easterly), there was net landward displacement that averaged -8.90 m of landward displacement. Farther downdrift, structures in the western portion of Fort Tilden trapped sediment that caused seaward displacement of +10 m to +20 m over the 4-year period. During this time period, the mean change was +3.54 m. A histogram of the distribution of dimensions of change was positively skewed with a bimodal characteristic (Figure 14). The greatest

peak, from 0 to +2 m, within the uncertainty, represented the eastern portion of the shoreline that was the most sheltered and had minimal shoreline displacement. The lesser peak in the distribution had a range of -8 m to -12 m, greater than the ± 3 m uncertainty value, and represented the shoreline position near the center portion of Breezy Point Cooperative.

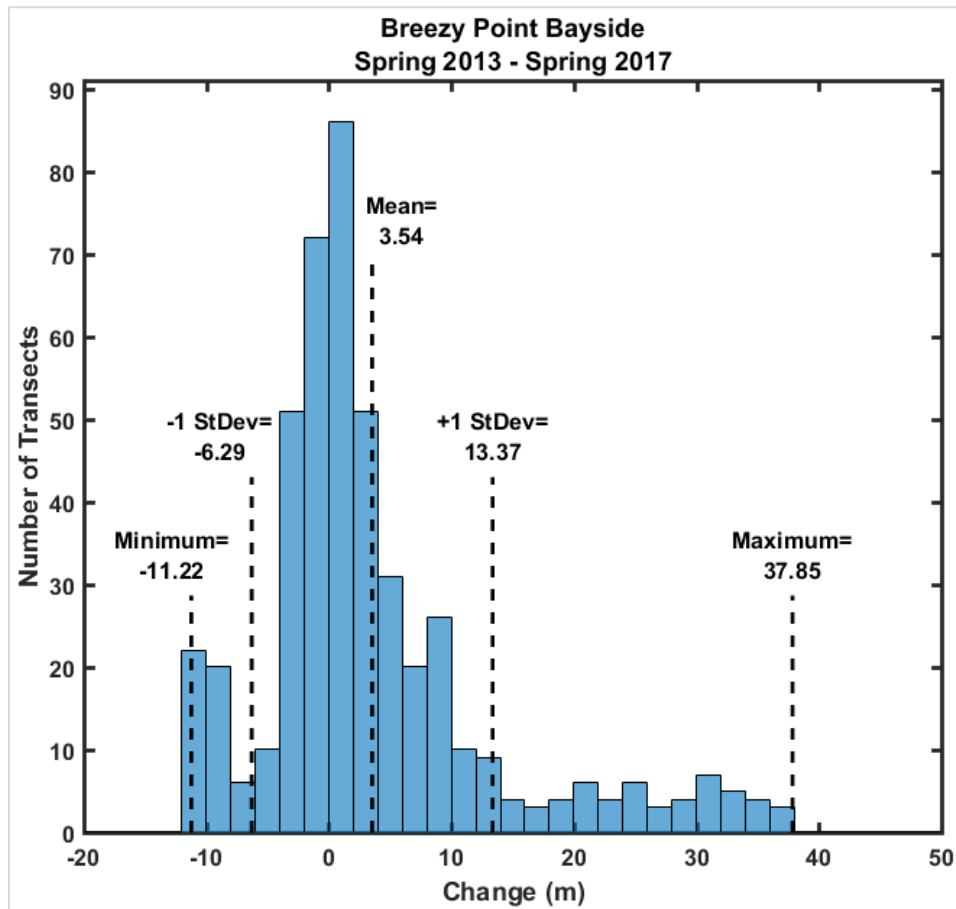


Figure 14. Histogram of vectors of shoreline change at Breezy Point Bayside, Gateway National Recreation Area, from Spring 2013 to Spring 2017.

Summary Statistics Tables and Trends of Change

The Breezy Point Bayside data are assembled to represent seasonal, annual, and 4-year metrics of shoreline change (Table 6). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics varied from -4.37 m of landward displacement (Fall 2012 – Spring 2013) to +4.40 m of seaward displacement (Spring 2012 – Fall 2012). There was net seaward displacement in the first three annual comparisons from Spring 2012 – Spring 2015 and net landward displacement from Spring 2015 to Spring 2017. The maximum mean displacement of +2.91 m occurred in Spring 2014 – Spring 2015 (Table 6).

Table 6. Seasonal, annual, and 4-year metrics of shoreline change for Breezy Point Bayside, Gateway National Recreation Area, 2013 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012**	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012*	4.40	–	12.87	27.09	-32.29
	Fall 2012 - Spring 2013	-4.37	–	7.38	14.54	-20.65
	Spring 2013 - Fall 2013	3.55	3.55	7.62	29.00	-16.23
	Fall 2013 - Spring 2014	-2.16	1.39	7.72	21.31	-29.98
	Spring 2014 - Fall 2014	1.00	2.39	4.34	18.61	-13.31
	Fall 2014 - Spring 2015	1.91	4.30	4.91	21.52	-17.38
	Spring 2015 - Fall 2015	-2.16	2.13	5.50	15.38	-20.04
	Fall 2015 - Spring 2016	1.62	3.75	5.73	25.59	-21.71
	Spring 2016 - Fall 2016	-3.78	-0.03	10.99	51.31	-29.91
	Fall 2016 - Spring 2017	3.56	3.53	5.45	27.75	-11.08
Annual	Spring 2012 - Spring 2013*	0.03	–	9.23	13.93	-20.71
	Spring 2013 - Spring 2014	1.39	1.39	5.03	18.37	-9.19
	Spring 2014 - Spring 2015	2.91	4.30	4.18	21.58	-8.33
	Spring 2015 - Spring 2016	-0.55	3.75	5.27	22.75	-18.21
	Spring 2016 - Spring 2017	-0.22	3.53	9.22	48.81	-19.87
Net	Spring 2013 - Spring 2017	3.53	3.53	9.82	37.85	-11.22

* indicates that there is a gap in the shoreline data during the specified time period, only transects without data gaps used in the calculation of statistics.

** Due to a large data gap in Spring 2012 net displacement of shoreline is calculated from Spring 2013.

The net shoreline displacement starting with the Spring 2013 survey was also calculated for each successive seasonal, annual, and 4-year temporal span. Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement. However, the calculation requires comparable data sets with no gaps in shoreline position data. To apply net mean displacement analysis to the Breezy Point Bayside shoreline, only vectors of change that are present in every shoreline comparison were incorporated in the analysis.

Trends of the changes, expressed as a general rate of change per year, albeit not a predictive value, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Fall 2010 to the Spring 2017 survey (Figure 15). To best understand the effects of shoreline displacement and recovery on the overall linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provide greater detail. This analysis indicates that the mean shoreline position at Breezy Point Bayside was displaced seaward at the rate of +0.87 m/yr (Figure 15). The trend line fits the Breezy Point Bayside mean shoreline net displacement data well, due to sheltering of the bayside shoreline and lack of recent anthropogenic alterations. The rates of net

shoreline displacement from Fall 2010 to Spring 2013 and from Spring 2013 to Spring 2017 were both slightly seaward, +1.98 m/yr and +0.29 m/yr, respectively.

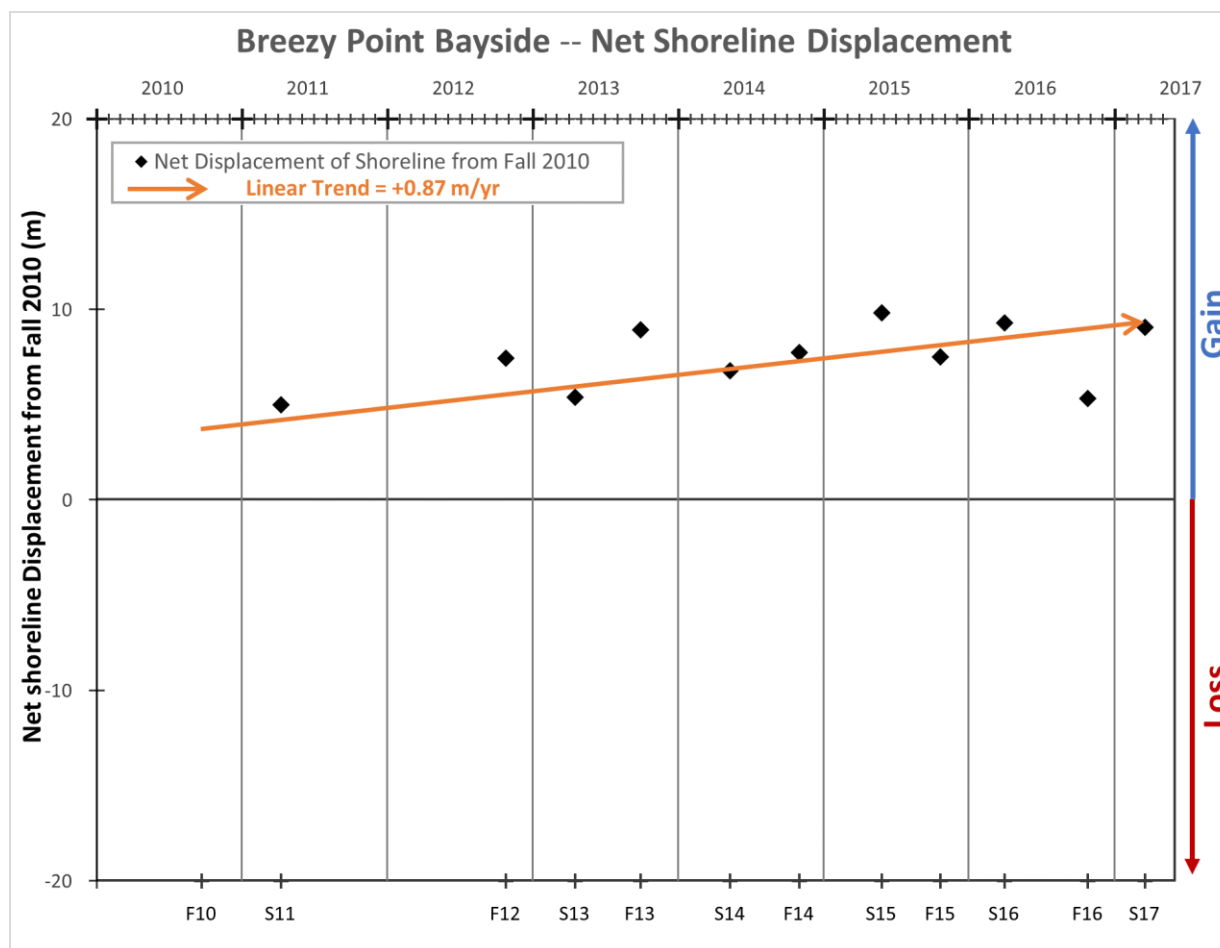


Figure 15. Trend of mean seasonal shoreline net displacement at Breezy Point Bayside, Gateway National Recreation Area, Spring 2010 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Plumb Beach

Plumb Beach is a sheltered ocean-facing site with limited exposure to incoming waves. The Western Portion of the site has a variety of structures and human modifications, and the Eastern Portion is downdrift of the structures and constitutes a more natural environment. The dividing line between the two portions is about 300 m downdrift of the easternmost groin where the influence of the groin no longer affects the shoreline. Two permanent stone groins were constructed at the eastern and western margins of the nourishment area in 2013 (nourishment occurred in 2012), and a stone breakwater was emplaced offshore of the nourishment site (Figure 16) (USACE 2013). These structures limited some of the natural response to incident wave energy and sediment mobilization at the shoreline and caused localized displacement of the shoreline position. The direction of sediment transport is east to west, west of the stone breakwater and from west to east, east of the stone breakwater. Additional

detail on the sediment budget at Plumb Beach prior to the fill and stone breakwater emplacement is detailed in Psuty et al. (2014).

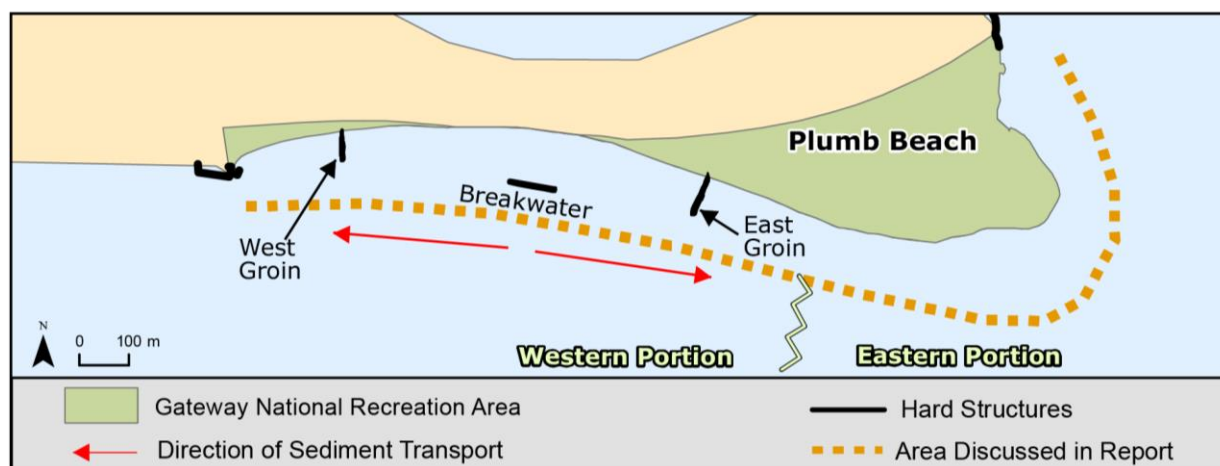


Figure 16. Features and descriptive characteristics of the Plumb Beach survey site, Jamaica Bay Unit, Gateway National Recreation Area.

Annual Shoreline Change

The shoreline at Plumb Beach was affected by the engineering structures in the park (Figure 16), relative storminess (Figure 2), and beach nourishment (Table 2). The Spring 2012 – Spring 2013 comparison had significant seaward displacement of the shoreline between the two groins, on the order of +50 m seaward (Figure 17). The large seaward shoreline displacements were a product of the nourishment event that occurred in Fall 2012 (Table 2). The nourishment event placed 127,000 yds³ (97,000 m³) of fill in the Western Portion and was completed prior to Hurricane Sandy.

The shoreline was displaced seaward consistently between +10 m and +20 m directly updrift of the eastern groin and inland of the breakwater in all annual comparisons except Spring 2016 – Spring 2017. This seaward displacement was due to the breakwater structure reducing incident wave energy inland of the breakwater and from the eastern groin trapping the eastward directed sediment. The remaining shoreline in the Western Portion fluctuated between moderate landward displacement (2013 – 2014 and 2016 – 2017) with displacements of -5 m to -15 m and relatively stable or smaller displacements (2014 – 2015 and 2015 – 2016) with displacements ranging from -0.5 m to -5 m (Figure 17). The areas of moderate landward displacement occurred on either side of the breakwater, due to sediment being directed away from the breakwater to both the east and west and occurred immediately downdrift of the eastern groin as a product of wave diffraction. In the Eastern Portion, there were seaward displacements of about +5 m to +15 m in most annual comparisons because it was beyond the effects of the eastern stone groin. Two exceptions were the Spring 2013 – Spring 2014 survey comparison and the southeastern point of the Spring 2012 – Spring 2013 comparison when there were landward displacements of -0.5 m to -5 m and -5 m to -10 m, respectively. The southeastern point of Plumb Beach varied from about -10 m to about +10 m of change throughout the annual comparisons (Figure 17).

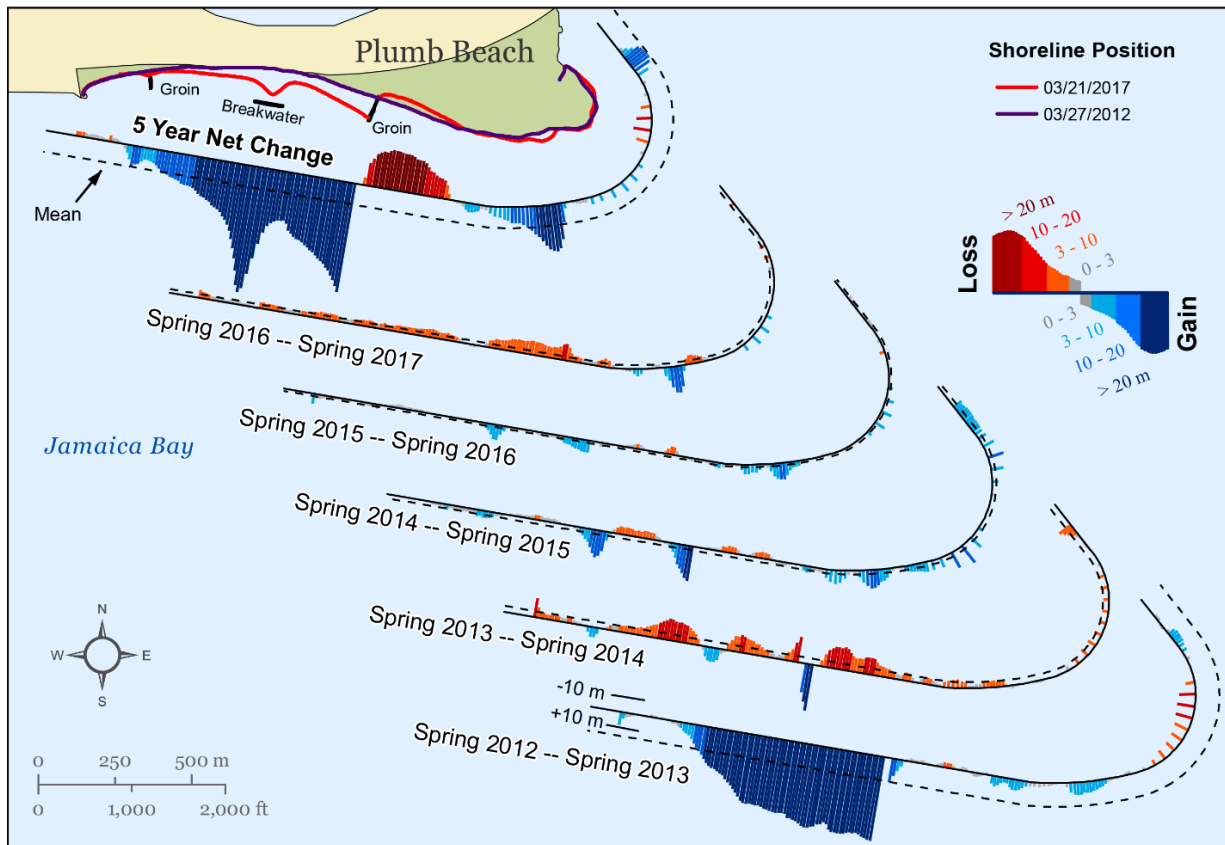


Figure 17. Distribution of annual and 5-year shoreline change at Plumb Beach, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the Spring 2012 – Spring 2013 comparison.

5-Year and Shoreline Change

The mean shoreline change at Plumb Beach over the 5-year period was +14.74 m. During the 5-year period, the majority of seaward displacement at Plumb Beach occurred between the two stone groins (Figure 17) due to the nourishment event. The shoreline located between the two stone groins was previously dominated by landward displacement before the fill and emplacement of structures (Psuty et al. 2014). The local 5-year maximum seaward displacements of +82.74 and +71.64 m occurred inland of the breakwater and eastern groin, respectively. Downdrift of the eastern groin, moderate landward displacement (with a maximum landward displacement of -25.72 m) decreased and transitioned to moderate seaward displacement (seaward displacements of +25 m to +30 m) with increasing distance from the groin structure. The amount of landward displacement immediately downdrift of the eastern groin increased from about -5 m to -10 m in Fall 2008 to Fall 2012 (Psuty et al. 2014) to a range of -15 m to -25 m from Spring 2012 to Spring 2017.

As the shoreline approached the deep channel at the southeastern tip of Plumb Beach, the seaward displacement of the shoreline was reduced (seaward displacements about +7 m) and transitioned into landward displacements around -10 m. The inlet facing shoreline at the northeast-facing terminus had net seaward displacements of +10 m to +15 m over the 5-year period (Figure 17). A histogram of the distribution of dimensions of change was positively skewed with a bimodal characteristic (Figure

18). The greatest peak, from 0 m to +10 m, represented most of the seaward displacement that occurred in the Eastern Portion of the site as sediment was transported downdrift, away from the eastern groin. The lesser peak in the distribution had a range of -20 m to -25 m, greater than the ± 3 m of uncertainty, and represented the landward displacement that occurred immediately downdrift of the eastern groin.

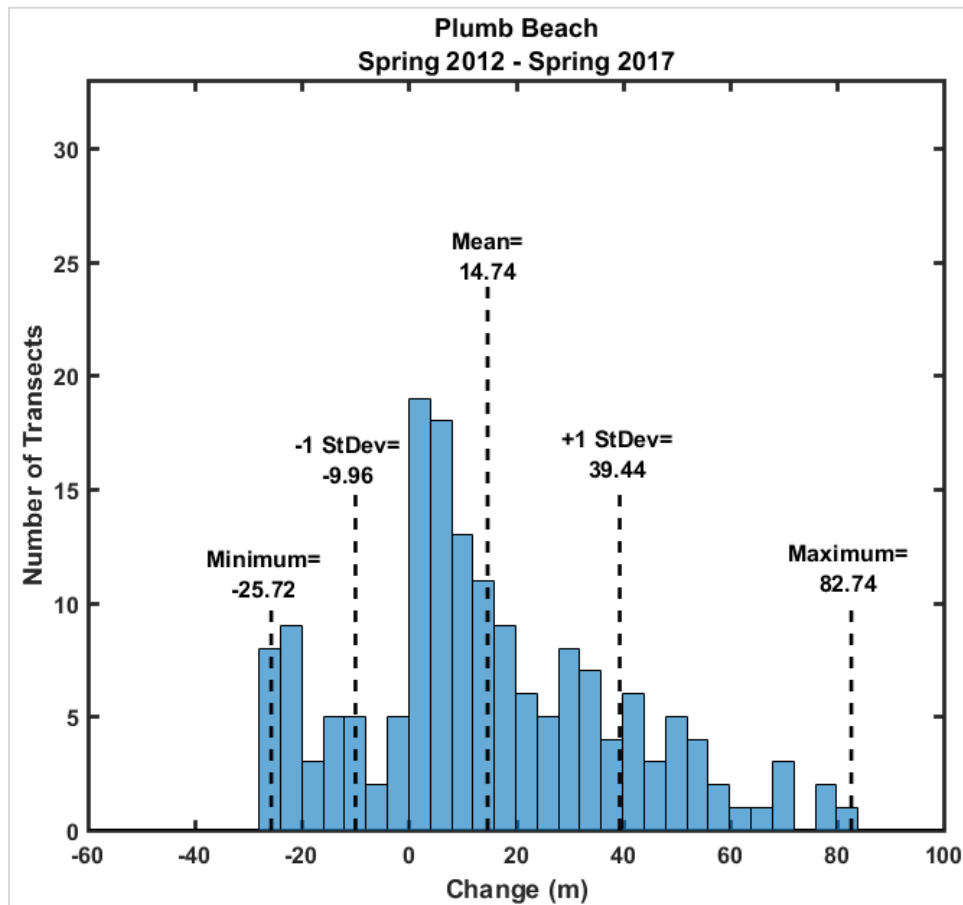


Figure 18. Histogram of vectors of shoreline change at Plumb Beach, Gateway National Recreation Area, from Spring 2012 to Spring 2017.

4-Year Post-Nourishment Shoreline Change

A 4-year post nourishment shoreline change analyses, Spring 2013 – Spring 2017, was completed to separately depict the changes associated with the construction of the two stone groins and the offshore breakwater. From Spring 2013 – Spring 2017 the shoreline displacement between the two stone groins was dominantly landward (Figure 19). Most vectors of change were between -10 m and -20 m of landward displacement. An exception was opposite of the breakwater where seaward displacement ranged from +15 m to +30 m. The seaward displacement immediately updrift of the eastern stone groin was due to the removal of the temporary groin, and placement of the stone groin in 2013. The placement of the stone groin downdrift of the temporary groin's position stopped any landward displacement downdrift of the temporary groin and allowed sediment to collect on the

updrift side of the stone groin (Figure 19). Shoreline change downdrift of the two stone groins was comparable to that of the 5-year shoreline change analysis.

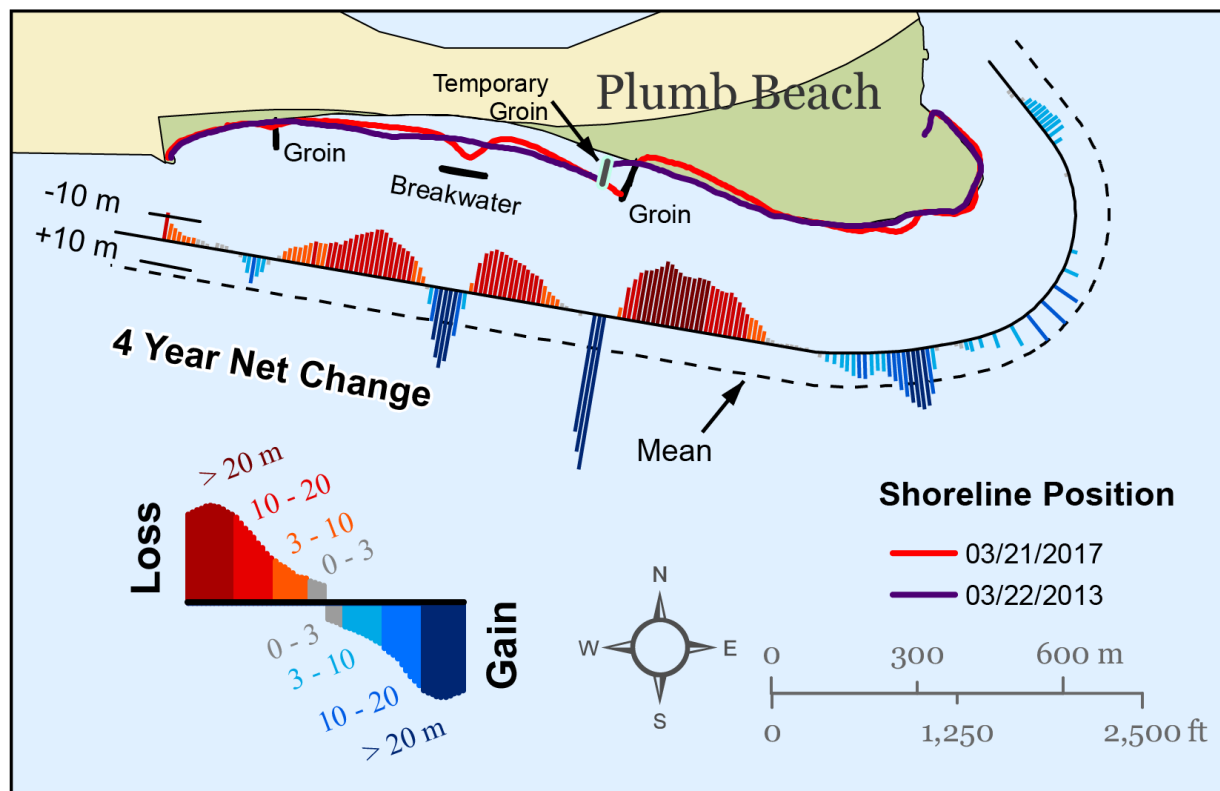


Figure 19. Distribution of 4-year shoreline change at Plumb Beach, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the 4-year net change comparison.

Summary Statistics Tables and Trends of Change

The Plumb Beach data are assembled to represent seasonal, annual, and 5-year metrics of shoreline change (Table 7). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics varied from -8.34 m of landward displacement (Spring 2016 – Fall 2016) to +5.73 m of seaward displacement (Fall 2016 – Spring 2017). There was a mean seaward displacement of +17.64 m, in the first annual comparison (Spring 2012 – Spring 2013). The annual means of all the other annual comparisons were much less in magnitude and varied in displacement direction, ranging from -4.40 m landward (Spring 2013 – Spring 2014) to +2.55 m seaward (Spring 2014 – Spring 2015) (Table 7).

Table 7. Seasonal, annual, and 5-year metrics of shoreline change for Plumb Beach, Gateway National Recreation Area, 2012 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012*	–	–	–	–	–
	Fall 2012 - Spring 2013*	–	17.64**	–	–	–
	Spring 2013 - Fall 2013	-5.24	12.40	3.72	4.53	-26.76
	Fall 2013 - Spring 2014	0.84	13.24	3.79	20.17	-7.69
	Spring 2014 - Fall 2014	-1.92	11.32	3.11	8.31	-8.22
	Fall 2014 - Spring 2015	4.47	15.79	4.06	20.63	-2.19
	Spring 2015 - Fall 2015	-1.17	14.62	2.07	3.52	-12.58
	Fall 2015 - Spring 2016	2.72	17.34	2.88	12.92	-1.66
	Spring 2016 - Fall 2016	-8.34	9.00	2.13	–	-15.02
	Fall 2016 - Spring 2017	5.73	14.74	4.69	23.41	-1.91
Annual	Spring 2012 - Spring 2013	17.64	17.64	22.14	55.61	-11.77
	Spring 2013 - Spring 2014	-4.40	13.25	5.67	24.71	-16.58
	Spring 2014 - Spring 2015	2.55	15.80	5.33	22.93	-5.21
	Spring 2015 - Spring 2016	1.55	17.35	2.90	10.78	-5.31
	Spring 2016 - Spring 2017	-2.61	14.74	4.40	17.41	-10.76
Net	Spring 2012 - Spring 2017	14.74	14.74	24.70	82.74	-25.72

* Shoreline data were not collected Fall 2012

** Spring 2012 – Spring 2013 mean net displacement of shoreline

The net shoreline displacement starting with the Spring 2012 survey was also calculated for each successive seasonal, annual, and 5-year temporal span. Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement. However, the calculation requires comparable data sets with no gaps in shoreline position data. To apply net mean displacement analysis to the shoreline of Plumb Beach, only vectors of change that are present in every shoreline comparison were incorporated in the analysis.

Trends of the changes, expressed as a general rate of change per year, albeit not a predictive value, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Spring 2008 to the Spring 2017 survey (Figure 20). The trend was calculated pre- and post-nourishment at Plumb Beach to make meaningful comparisons (e.g., having a trend line that is not largely skewed by the nourishment event). To best understand the effects of shoreline displacement and recovery on the linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provided greater detail. This analysis indicates that the mean shoreline position, pre-nourishment was displaced seaward at the rate of +0.09 m/yr, and post-nourishment was displaced landward at the rate of -0.53 m/yr post-nourishment (Figure 20). The greatest difference between the

net displacement points and the linear regression lines occurred in Fall 2010 and Post-Storm 2010 as well as Spring 2016 and in Fall 2016 due to storm events affecting the natural trend of the shoreline displacement.

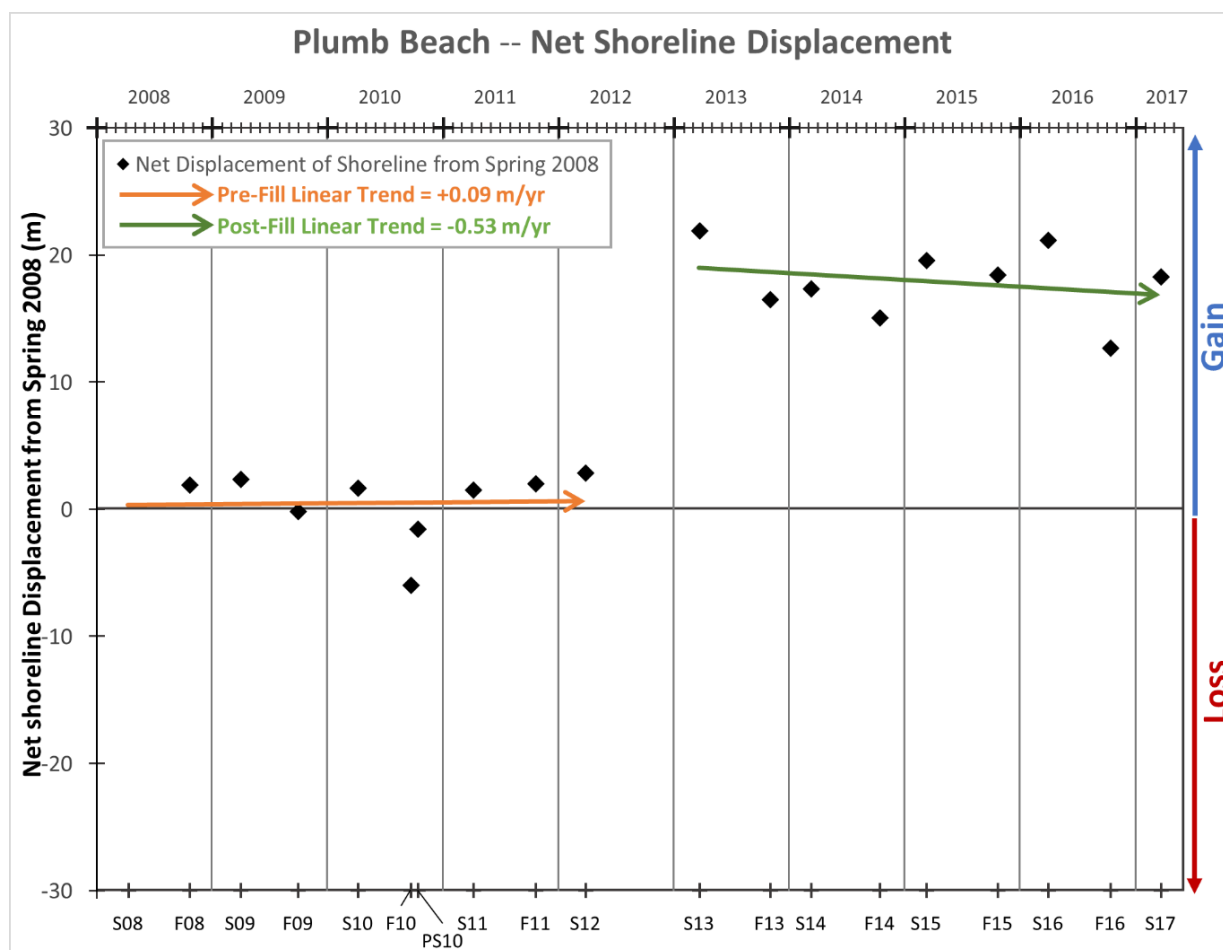


Figure 20. Trend of mean seasonal shoreline net displacement at Plumb Beach, Gateway National Recreation Area, Spring 2008 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Staten Island Unit

Great Kills

Great Kills is located along Staten Island and is shielded from direct ocean wave exposure because waves entering Raritan Bay via the gap between Sandy Hook and Breezy Point are partially filtered, diffracted, and refracted before arriving at the site. The Great Kills shoreline is separated into two segments: 1) ocean-facing; and 2) bay-facing. Sediment input from updrift (northeast) is limited by a series of groins in the communities as well as by a water treatment outfall pipe that serves as a large terminal groin near the park boundary (Figure 21). The northeastern portion of the ocean-facing shoreline is also partially shielded from the incident waves by remnants of an ancestral marsh and further modified inland by landfill that creates an artificial headland bluff 2-5 m in elevation. The

southwestern end of Great Kills Park has a jetty that separates the ocean-facing shoreline from the bayside shoreline. Northwest of the jetty there is a protruding node, composed of a southern-facing limb and western-facing limb, that was partially removed during a dredging event of Great Kills Harbor in 2014. The sediment transport direction at Great Kills is northeast to southwest. A more detailed understanding of the sediment budget at Great Kills is described in Psuty et al. (2016b).

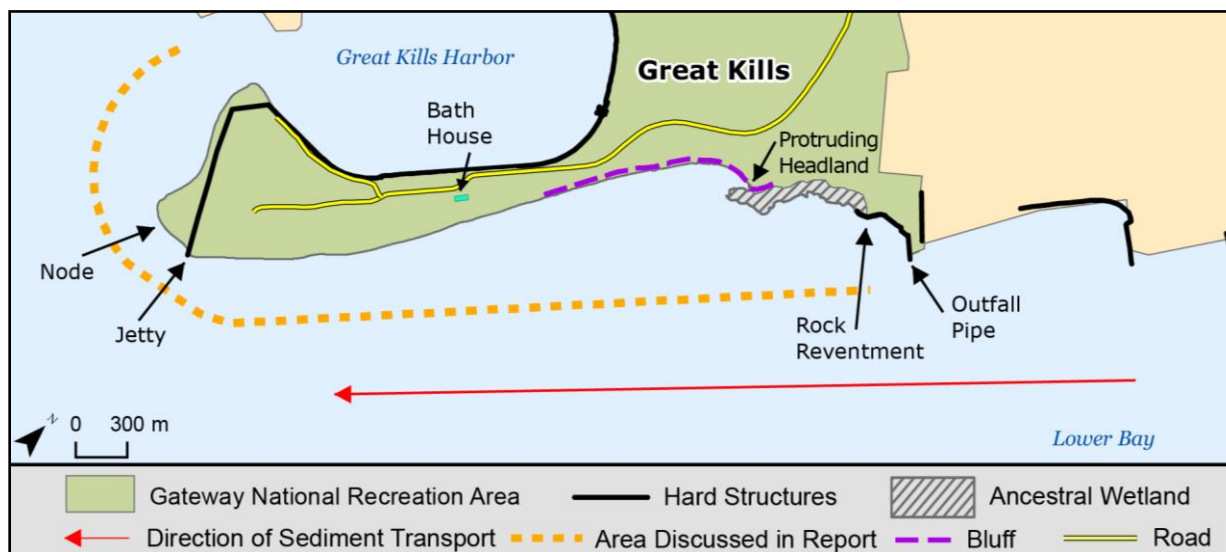


Figure 1. Features and descriptive characteristics of the Great Kills survey site, Staten Island Unit, Gateway National Recreation Area.

Great Kills Oceanside

Annual Shoreline Change

The shoreline at Great Kills was affected by remnants of the ancestral wetland, extensive landfill, and engineering structures in and updrift of the park (Figure 21), interacting with the relative storminess (Figure 2). Landward displacement along nearly the entire ocean-facing shoreline occurred in Spring 2012 – Spring 2013 with a mean displacement of -4.99 m landward (Figure 22). The shoreline-wide landward displacement in the Spring 2012 – Spring 2013 comparison was due to the occurrence of Hurricane Sandy. However, the landward displacement in the Spring 2016 – Spring 2017 period was the most extensive throughout the site of all annual comparisons, a mean displacement of -5.05 m landward due to storminess and lack of sediment availability. Three consecutive annual comparisons incorporating Spring 2013 – Spring 2014, Spring 2014 – Spring 2015 and Spring 2015 – Spring 2016 had very similar displacement patterns. The first similarity was in the extreme northeastern end of the shoreline where the shoreline was relatively stable due to a stone riprap wall and a salt marsh edge. The average annual displacement in this portion of the shoreline was -0.03 m (2013 – 2014), +0.68 m (2014 – 2015), and +1.78 m (2015 – 2016), an average of +0.81 m of seaward displacement over the three comparisons. The second similarity in the three annual comparisons (similar in all annual comparisons) was increased landward displacement at the protruding headland, with maximum landward displacement occurring at the southwestern margin of the protruding headland. The maximum landward displacements were -15.35 m (2013 – 2014), -16.33 m (2014 – 2015), and -

23.36 m (2015 – 2016). The increased landward displacement at and immediately downdrift of the protruding headland was related to the terminus of the marsh remnants lying offshore and their effect on buffering incident wave energy as well as to the outfall pipe that was limiting sediment from updrift. The last similarity of the three comparisons was downdrift of the protruding headland where the landward displacement decreased to the west and eventually either stabilized and/or had seaward displacement, on the order of +1 m to +5 m (Figure 22).

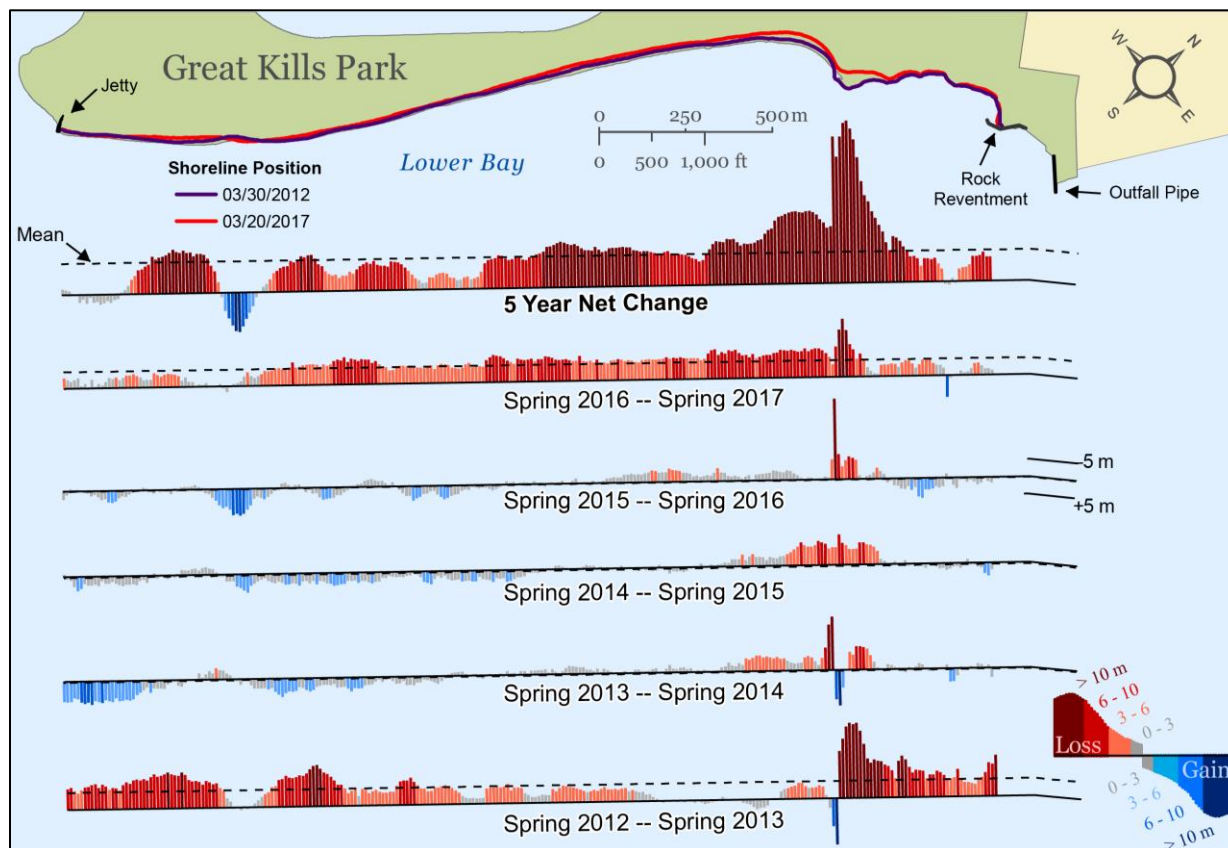


Figure 22. Distribution of annual and 5-year shoreline change at Great Kills, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the Spring 2015 – Spring 2016 comparison.

5-Year Shoreline Change

The entire shoreline, except small portions near the southwestern terminus, had landward displacement (Figure 22) over the 5-year period. The mean change at Great Kills Oceanside was - 8.93 m. whereas most of the erosive vectors of change were near the 5-year mean, the shoreline along the small protruding headland averaged -37.58 m of landward displacement. Immediately downdrift of the small headland, the average landward displacement was -18.75 m (Figure 22). Near the jetty in the southwest, the shoreline remained relatively stable with displacements between -1 m and +2 m and a small portion of shoreline updrift of the jetty had accreted on the order of +10 m. Overall, the Great Kills Oceanside did not recover from Hurricane Sandy, but instead had increased landward displacement across the site after the storm. A histogram of the distribution of dimensions

of change was negatively skewed with a unimodal characteristic (Figure 23). The peak, from -10 m to -12 m, greater than the ± 3 m uncertainty value, represented the majority of vectors of change on the Great Kills Oceanside shoreline except near the protruding headland (Figure 22). The negative skew represented the shoreline near the protruding headland that had increased landward displacement over the 5-year period, a maximum landward displacement of -46.73 m (Figure 23).

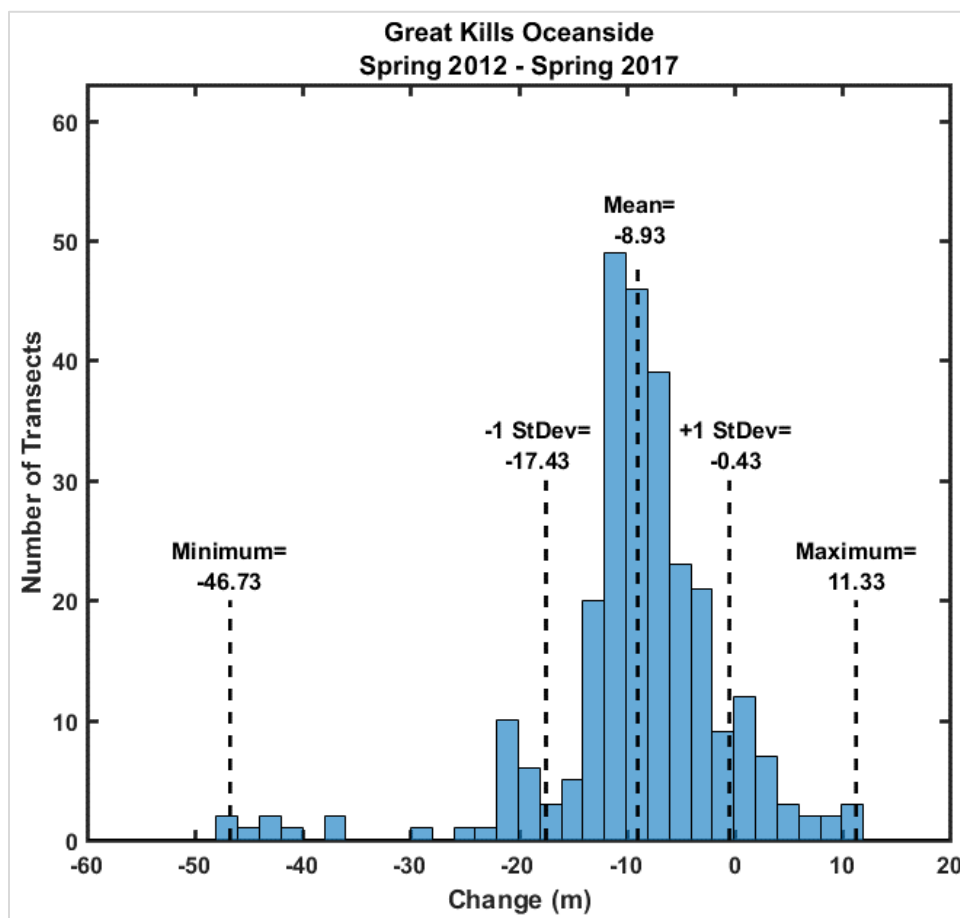


Figure 23. Histogram of vectors of shoreline change, from Spring 2012 to Spring 2017 at Great Kills Oceanside, Gateway National Recreation Area.

Summary Statistics Tables and Trends of Change

The Great Kills Oceanside data are assembled to represent seasonal, annual, and 5-year metrics of shoreline change (Table 8). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics varied from -3.90 m of landward displacement (Spring 2016 – Fall 2016) to +1.51 m of seaward displacement (Fall 2014 – Spring 2015). There was mean landward displacement of -4.99 m, in the first annual comparison (Spring 2012 – Spring 2013) and the last annual comparison, -5.05 m (Spring 2016 – Spring 2017). There was mean seaward displacement in all other annual comparisons, although the maximum mean displacement was +0.47 m that occurred in Spring 2013 – Spring 2014 (Table 8).

Table 8. Seasonal, annual, and 5-year metrics of shoreline change for Great Kills Oceanside, Gateway National Recreation Area, 2012 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012	-1.88	-1.88	1.56	1.22	-7.25
	Fall 2012 - Spring 2013	-3.11	-4.99	4.17	14.72	-20.10
	Spring 2013 - Fall 2013	0.23	-4.76	3.71	20.29	-14.82
	Fall 2013 - Spring 2014	0.24	-4.52	3.85	50.22	-10.01
	Spring 2014 - Fall 2014	-1.20	-5.73	1.68	6.09	-8.13
	Fall 2014 - Spring 2015	1.51	-4.22	2.27	5.51	-17.00
	Spring 2015 - Fall 2015	-0.62	-4.84	3.17	7.88	-21.52
	Fall 2015 - Spring 2016	0.96	-3.88	5.88	82.73	-27.34
	Spring 2016 - Fall 2016	-3.90	-7.78	4.83	20.36	-73.90
	Fall 2016 - Spring 2017	-1.16	-8.93	3.00	5.42	-19.25
Annual	Spring 2012 - Spring 2013	-4.99	-4.99	4.43	13.37	-21.65
	Spring 2013 - Spring 2014	0.47	-4.52	4.10	44.38	-15.35
	Spring 2014 - Spring 2015	0.31	-4.22	2.76	5.31	-16.33
	Spring 2015 - Spring 2016	0.34	-3.88	5.95	84.47	-23.36
	Spring 2016 - Spring 2017	-5.05	-8.93	5.39	6.30	-82.66
Net	Spring 2012 - Spring 2017	-8.93	-8.93	8.50	11.33	-46.73

The net shoreline displacement starting with the Spring 2012 survey was also calculated for each successive seasonal, annual, and 5-year temporal span. Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement.

Trends of the changes, expressed as a general rate of change per year, albeit not a predictive value, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Spring 2008 to the Spring 2017 survey (Figure 24). To best understand the effects of shoreline displacement and recovery on the overall linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provided greater detail. This analysis indicated that the mean shoreline position at Great Kills Oceanside was displaced landward at the rate of -0.84 m/yr (Figure 24). There was increased difference between the net displacement points and the linear regression line in Spring 2013 and Spring 2016, a function of increased storminess (including Hurricane Sandy) affecting the natural trend of the shoreline displacement. From Spring 2008 to Spring 2012 there was a small seaward displacement rate of +0.02 m/yr, from Spring 2012 to Spring 2017 there was a landward displacement rate of -1.20 m/yr.

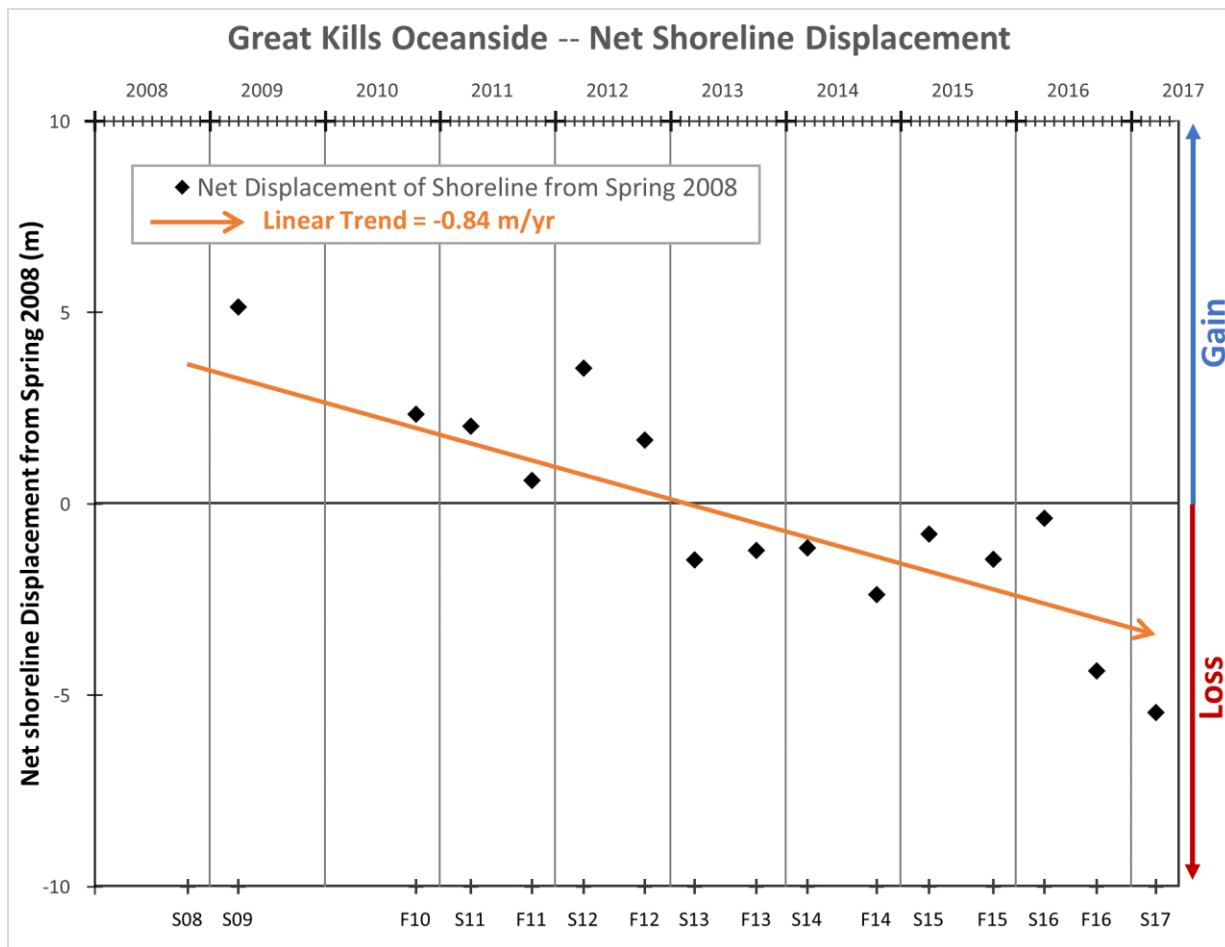


Figure 24. Trend of mean seasonal shoreline net displacement at Great Kills Oceanside, Gateway National Recreation Area, Spring 2008 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Great Kills Bayside

Annual Shoreline Change

The bayside shoreline at Great Kills was affected by relative storminess (Figure 2), sediment getting around the jetty (Figure 21), and by the dredging of Great Kills Harbor entrance west of the jetty (Table 2). In the Spring 2012 – Spring 2013 comparison there was landward displacement of about -20 m to -30 m on the southern-facing limb of the node, and seaward displacement on the west-facing limb of the node on the order of +10 m to +20 m (Figure 25). Increased storminess (including Hurricane Sandy) and the difference in shoreline orientation (between the southern-facing and west-facing limbs of the node) influenced the displacements in the Spring 2012 – Spring 2013 comparison. The Spring 2013 – Spring 2014 and Spring 2016 – Spring 2017 comparisons had seaward displacements of +5 m to +8 m along the western-facing limb of the node and had relatively calm stormy seasons. In Spring 2014, dredging of Great Kills Harbor channel occurred that included removal of sediment from the node, thereby modifying the dimension and extent of the node and displacing the shoreline. The Spring 2014 – Spring 2015 annual comparison recorded a maximum landward displacement of -113.46 m (Figure 25). Spring 2015 – Spring 2016 had marginal

displacements ranging from -2 m to +4 m, except in the area of the newly (post-dredging) accreting node. The 2015 – 2016 winter season was particularly stormy and had seaward displacement of +20 m to +30 m along the west shoreline of the accreting node, similar to Spring 2012 – Spring 2013. There was also +5 m to +15 m of seaward displacement on the southern-facing limb of the node due to sediment making it around the jetty.

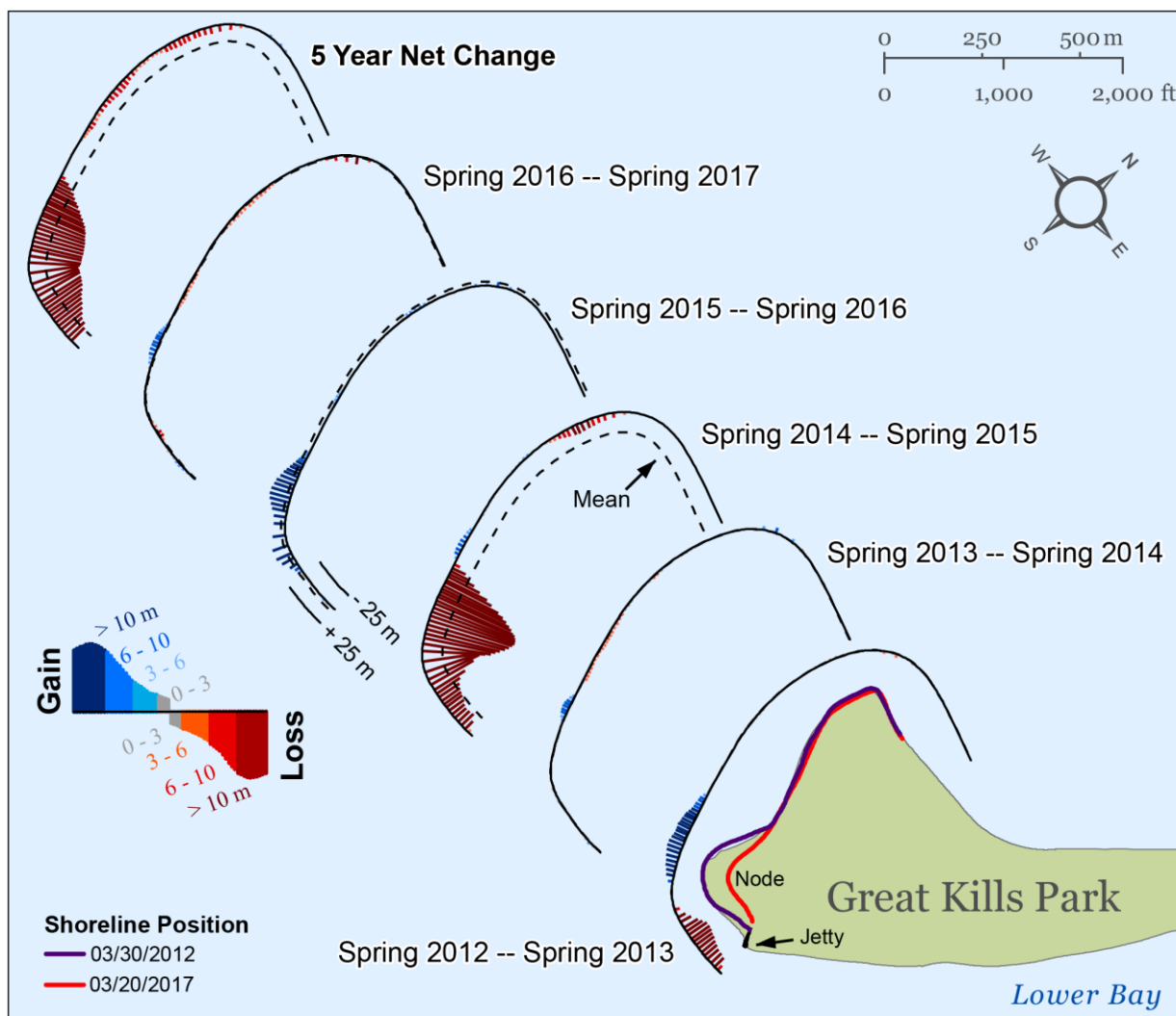


Figure 25. Distribution of annual and 5-year shoreline change at Great Kills Bayside, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the Spring 2014 – Spring 2015 comparison.

5-Year Shoreline Change

The entire shoreline, except the shoreline in the northeast, had landward displacement (Figure 25). The landward displacement increased dramatically from displacements of -5 m to -10 m on the west and northwestern portions of the shoreline to landward displacements of -30 m to -60 m about the node (Figure 25). The only seaward displacement occurred along the northeast portion of the shoreline where there were from about +1 m to +4 m. The mean change over the 5-year period was -

21.97 m. A histogram of the distribution of dimensions of change was negatively skewed with a bimodal characteristic (Figure 26). The greatest peak, from -5 m to -10 m, greater than the ± 3 m of uncertainty, represented most of the shoreline that was north of the node. A lesser peak, from -75 m to -85 m, represented the node in the shoreline near the jetty that eroded with help from storm events and the dredging event.

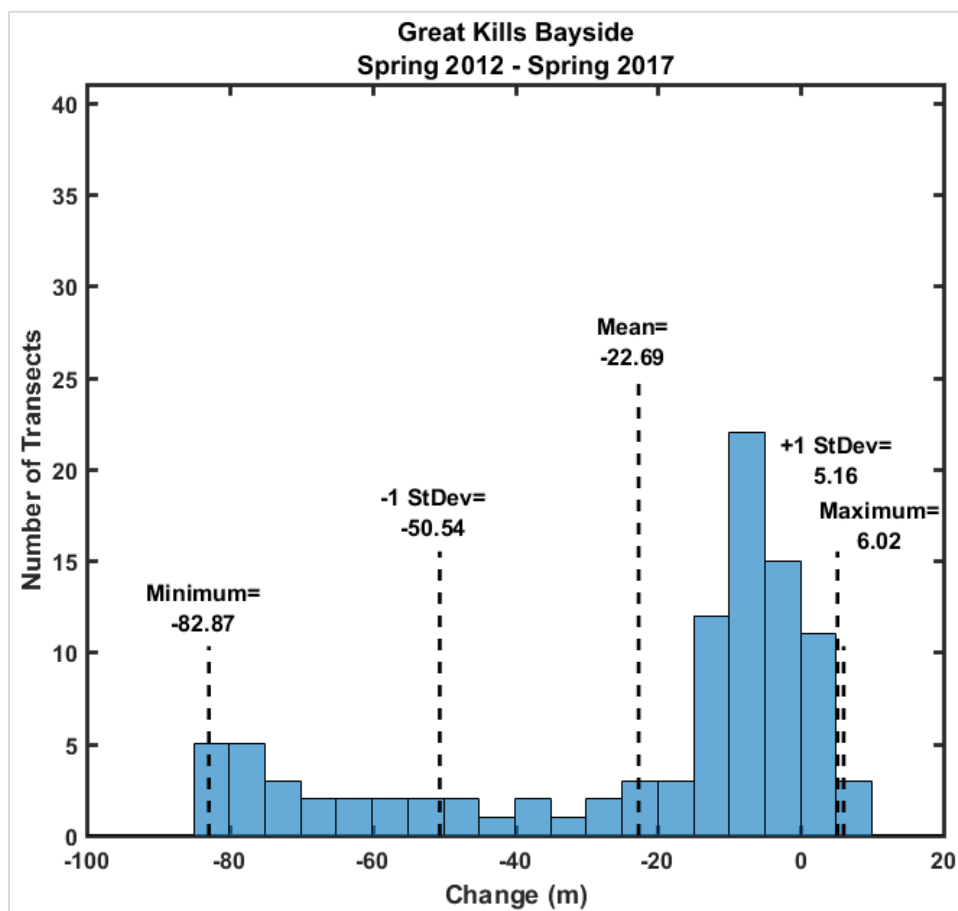


Figure 26. Histogram of vectors of shoreline change, from Spring 2012 to Spring 2017 at Great Kills Bayside, Gateway National Recreation Area.

Summary Statistics Tables and Trends of Change

The Great Kills Bayside data are assembled to represent seasonal, annual, and 5-year metrics of shoreline change (Table 9). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics varied from -25.98 m of landward displacement (Spring 2014 – Fall 2014) to +5.11 m of seaward displacement (Fall 2015 – Spring 2016). The annual mean metrics were similar to the seasonal mean metrics and varied from -26.40 m of landward displacement (Spring 2014 – Spring 2015) to +5.15 m of seaward displacement (Spring 2015 – Spring 2016) (Table 9).

Table 9. Seasonal, annual, and 5-year metrics of shoreline change for Great Kills Bayside, Gateway National Recreation Area, 2012 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012	3.30	3.30	4.20	14.22	-5.61
	Fall 2012 - Spring 2013	-2.58	0.72	7.43	10.87	-23.94
	Spring 2013 - Fall 2013	-0.34	0.38	2.50	7.24	-6.86
	Fall 2013 - Spring 2014	0.03	0.40	1.99	6.15	-4.18
	Spring 2014 - Fall 2014	-25.98	-25.58	39.94	12.57	-116.82
	Fall 2014 - Spring 2015	-0.42	-26.00	3.03	7.63	-5.31
	Spring 2015 - Fall 2015	0.04	-25.96	5.45	16.21	-10.34
	Fall 2015 - Spring 2016	5.11	-20.84	4.97	20.06	-1.91
	Spring 2016 - Fall 2016	-0.35	-21.20	3.49	6.62	-11.46
	Fall 2016 - Spring 2017	-0.78	-21.97	3.68	15.46	-7.23
Annual	Spring 2012 - Spring 2013	0.72	0.72	10.80	19.08	-28.17
	Spring 2013 - Spring 2014	-0.32	0.40	3.29	8.77	-5.16
	Spring 2014 - Spring 2015	-26.40	-26.00	38.86	7.93	-113.46
	Spring 2015 - Spring 2016	5.15	-20.84	7.79	27.01	-2.50
	Spring 2016 - Spring 2017	-1.13	-21.97	3.92	8.64	-10.27
Net	Spring 2012 - Spring 2017	-21.97	-21.97	24.96	3.62	-66.63

The net shoreline displacement starting with the Spring 2012 survey was also calculated for each successive seasonal, annual, and 5-year temporal span. Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement.

Trends of the changes pre- and post-dredging, expressed as general rates of change per year, albeit not predictive values, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Fall 2008 to the Spring 2017 survey (Figure 27). Two trend lines, pre- and post-dredging, were calculated to analyze the difference and to make meaningful comparisons (e.g., having trend lines that are not largely skewed by a dredging event). To best understand the effects of shoreline displacement and recovery on the overall linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provided greater detail. This analysis indicated that the mean shoreline position at Great Kills Bayside was displaced seaward at the rate of +2.45 m/yr prior to the 2014 dredging event (Figure 27). After the dredging event, the mean shoreline position was displaced seaward at a similar rate of +2.54 m/yr. There was increased difference between the net displacement points and the linear regression lines in Spring 2010, Fall 2012, Fall 2015, and Spring 2016, a function of increased storminess (including Hurricane Sandy) affecting the natural trend of the shoreline displacement.

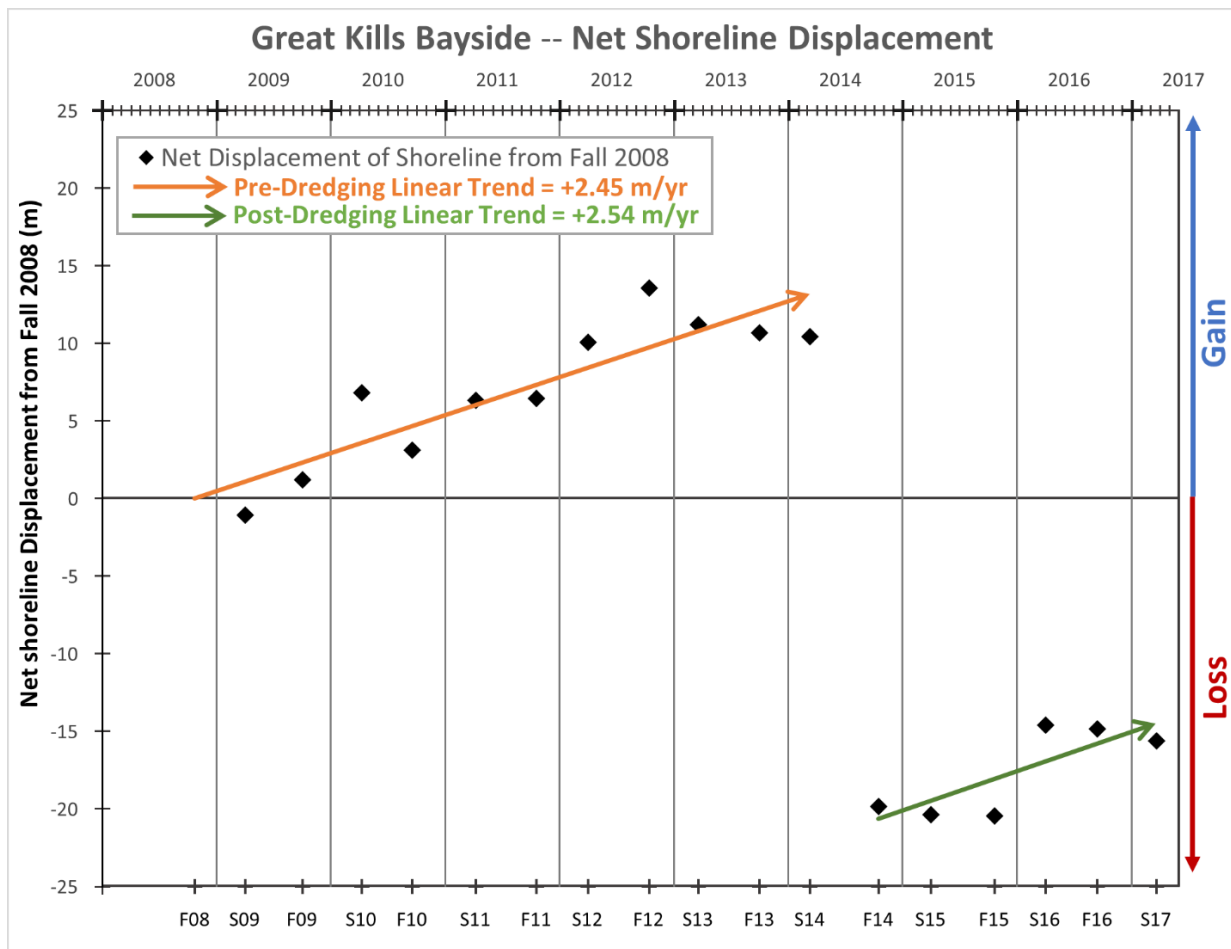


Figure 27. Trends of mean seasonal shoreline net displacement at Great Kills Bayside, Gateway National Recreation Area, Fall 2008 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Miller Field

Miller Field is located along Staten Island and is sheltered from direct ocean wave exposure in Lower Bay. The site is relatively short alongshore, about 0.6 km, and is positioned between two stone groins (Figure 28). The dominant direction of sediment transport at Miller Field varies between either northeasterly or southwesterly.

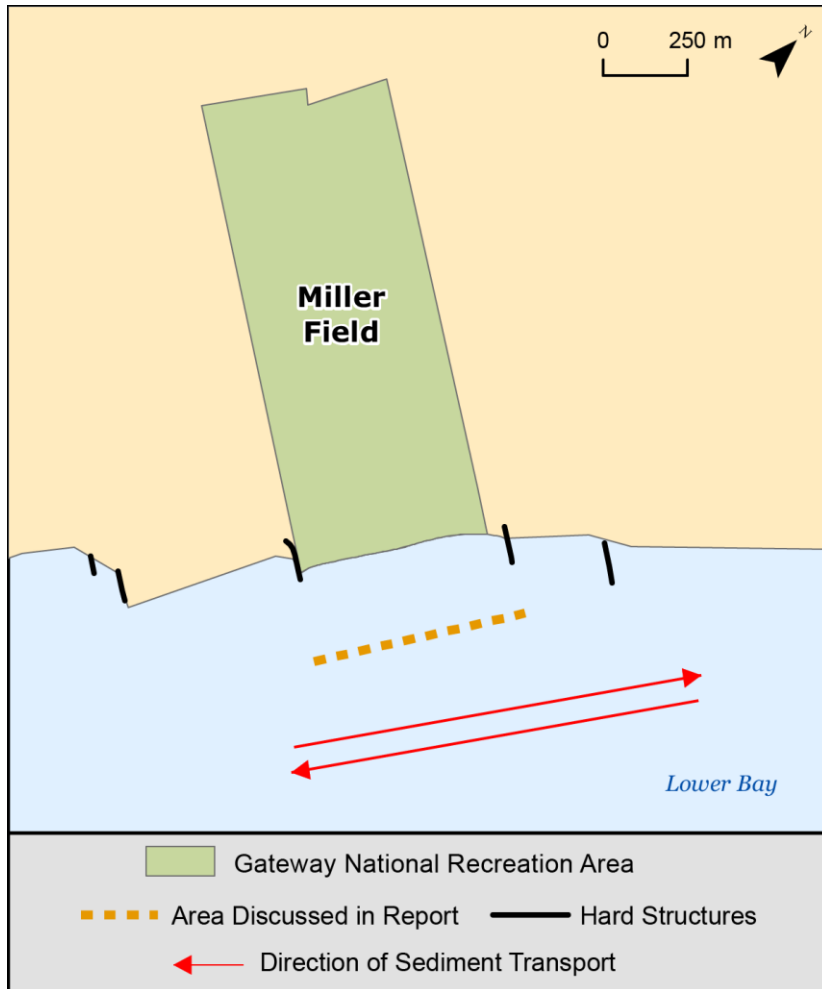


Figure 28. Features and descriptive characteristics of the Miller Field survey site, Staten Island Unit, Gateway National Recreation Area.

Annual Shoreline Change

The shoreline at Miller Field was affected by relative storminess (Figure 2) and strongly affected by the direction of alongshore transport due to being positioned between two groins (Figure 28). Thus, the several years of the survey had opposing conditions because the dominant sediment transport direction changed. Dominant sediment transport was directed southwesterly in Spring 2012 – Spring 2013 and Spring 2013 – Spring 2014 with landward displacements in both comparisons ranging from about -0.5 m to -5 m (Figure 29). In the two succeeding comparisons, all displacements were seaward associated with a northeasterly dominant sediment transport direction. In the Spring 2014 – Spring 2015 comparison, there were modest accretions of +1 m to +5 m and in the Spring 2015 – Spring 2016 comparison the magnitude of seaward displacement increased, ranging from about +5 m to +9 m related to increased storminess. The mean change in the Spring 2015 – Spring 2016 comparison was +6.53 m of seaward displacement. During the Spring 2016 – Spring 2017 comparison, the dominant sediment transport direction was to the southwest. The southwesterly sediment transport caused nearly uniform landward displacement along the Miller Field shoreline, a mean landward displacement of -11.66 m of (Figure 29).

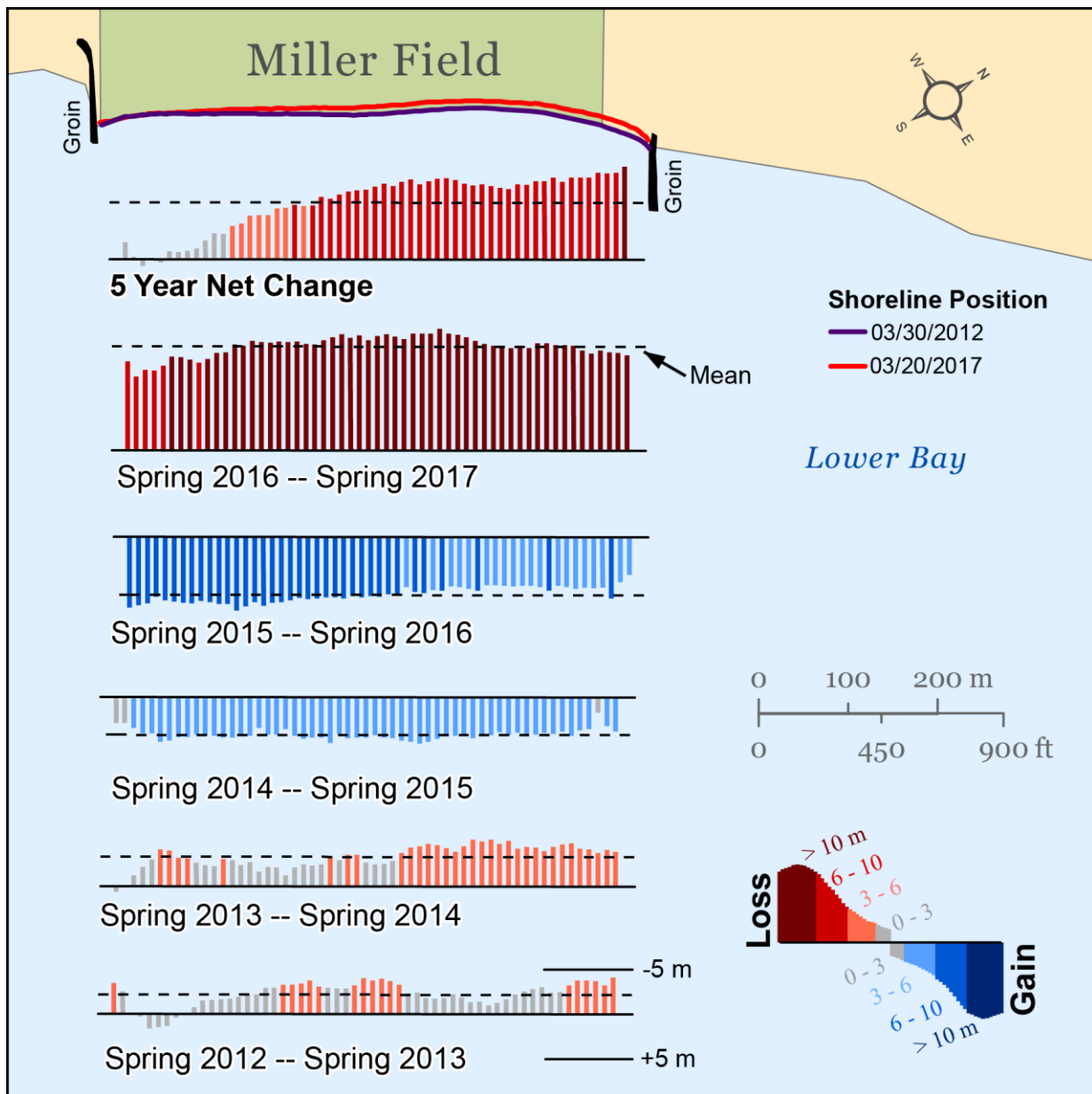


Figure 29. Distribution of annual and 5-year shoreline change at Miller Field, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the Spring 2012 – Spring 2013 comparison.

5-Year Shoreline Change

Nearly the entire Miller Field shoreline had landward displacement, increasing from southwest to northeast (Figure). The mean change over the 5-year period was -6.34 m. Toward the north, the Miller Field shoreline had greater landward displacement due to more years with dominant sediment transport pulling sediment away from the northeastern groin. The 5-year mean toward the north was -8.74 m of landward displacement compared to a mean of -3.86 m toward the south. The extreme southwestern portion of Miller Field was relatively stable over the 5-year period with displacements ranging from about -2 m to +1 m and a mean landward displacement of -0.31 m (Figure). A

histogram of the distribution of dimensions of change was positively skewed with a unimodal characteristic (Figur). The peak, from -8 m to -9 m, greater than the ± 3 m of uncertainty, represented the majority of vectors of change on the Miller Field shoreline, especially towards the north. The positive skew represented the steady decrease in magnitude toward the southern shoreline of Miller Field and near the southwestern groin where the maximum seaward displacement of +0.74 m occurred (Figur).

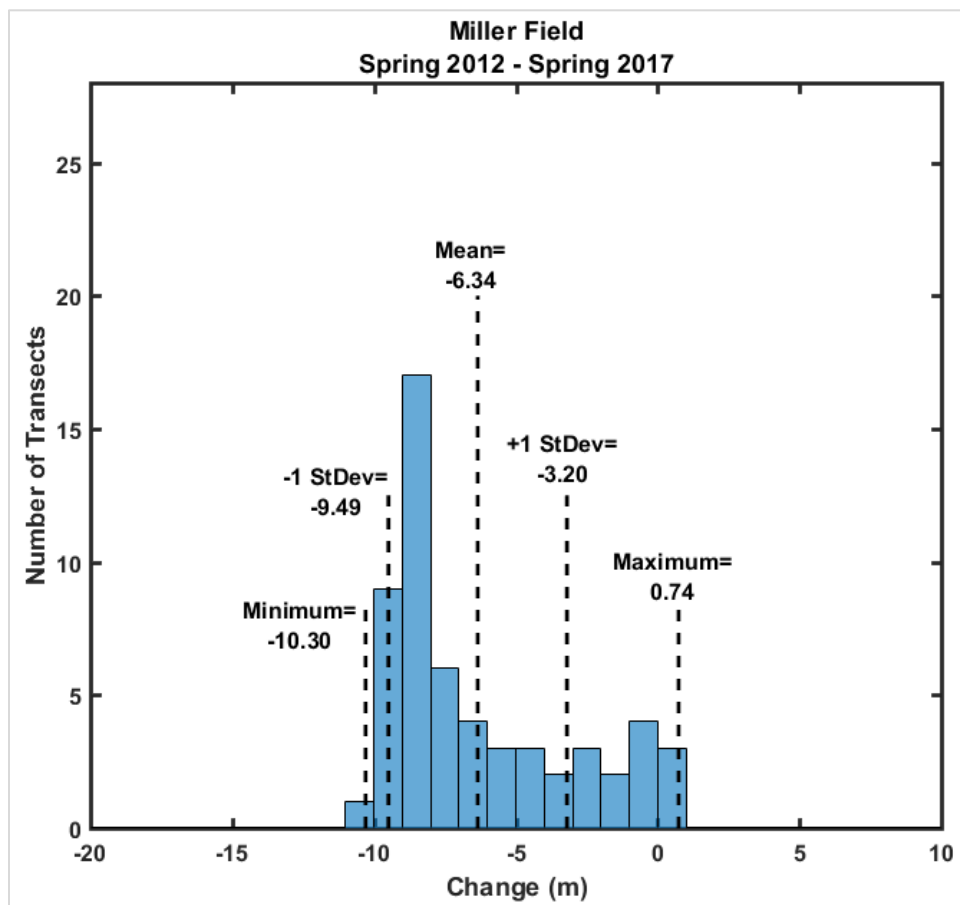


Figure 30. Histogram of vectors of shoreline change, from Spring 2012 to Spring 2017 at Miller Field, Gateway National Recreation Area.

Summary Statistics Tables and Trends of Change

The Miller Field data are assembled to represent seasonal, annual, and 5-year metrics of shoreline change (Table 10). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics varied from -12.44 m of landward displacement (Spring 2016 – Fall 2016) to +10.09 m of seaward displacement (Fall 2015 – Spring 2016). The annual mean metrics varied from -11.66 m of landward displacement (Spring 2016 – Spring 2017) to +6.53 m of seaward displacement (Spring 2015 – Spring 2016) (Table 10).

Table 10. Seasonal, annual, and 5-year metrics of shoreline change for Miller Field, Gateway National Recreation Area, 2012 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012	-1.07	-1.07	2.26	2.17	-7.71
	Fall 2012 - Spring 2013	-1.11	-2.18	2.94	5.36	-4.99
	Spring 2013 - Fall 2013	-4.68	-6.86	0.85	–	-7.42
	Fall 2013 - Spring 2014	1.39	-5.47	1.32	5.07	-0.58
	Spring 2014 - Fall 2014	-0.66	-6.13	1.74	1.60	-5.71
	Fall 2014 - Spring 2015	4.92	-1.21	1.56	9.17	–
	Spring 2015 - Fall 2015	-3.56	-4.77	0.72	–	-4.97
	Fall 2015 - Spring 2016	10.09	5.32	0.83	11.86	–
	Spring 2016 - Fall 2016	-12.44	-7.12	1.50	–	-15.47
	Fall 2016 - Spring 2017	0.78	-6.34	2.16	6.00	-2.10
Annual	Spring 2012 - Spring 2013	-2.18	-2.18	1.39	1.65	-4.04
	Spring 2013 - Spring 2014	-3.29	-5.47	1.25	0.66	-5.21
	Spring 2014 - Spring 2015	4.26	-1.21	0.59	5.24	–
	Spring 2015 - Spring 2016	6.53	5.32	0.87	8.29	–
	Spring 2016 - Spring 2017	-11.66	-6.34	1.16	–	-13.60
Net	Spring 2012 - Spring 2017	-6.34	-6.34	3.15	0.74	-10.30

The net shoreline displacement starting with the Spring 2012 survey was also calculated for each successive seasonal, annual, and 5-year temporal span. Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement.

Trends of the changes, expressed as a general rate of change per year, albeit not a predictive value, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Spring 2009 to the Spring 2017 survey (Figure 31). To best understand the effects of shoreline displacement and recovery on the overall linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provided greater detail. This analysis indicates that the mean shoreline position at Miller Field was displaced seaward at the rate of +0.18 m/yr (Figure 31). There was increased difference between the net displacement point and the linear regression line in Spring 2016, a function of storm events affecting the natural trend of the shoreline displacement. From Spring 2009 to Spring 2012, there was seaward net displacement rate of +1.49 m/yr, and from Spring 2012 to Spring 2017 there was a landward net displacement rate of -0.46 m/yr.

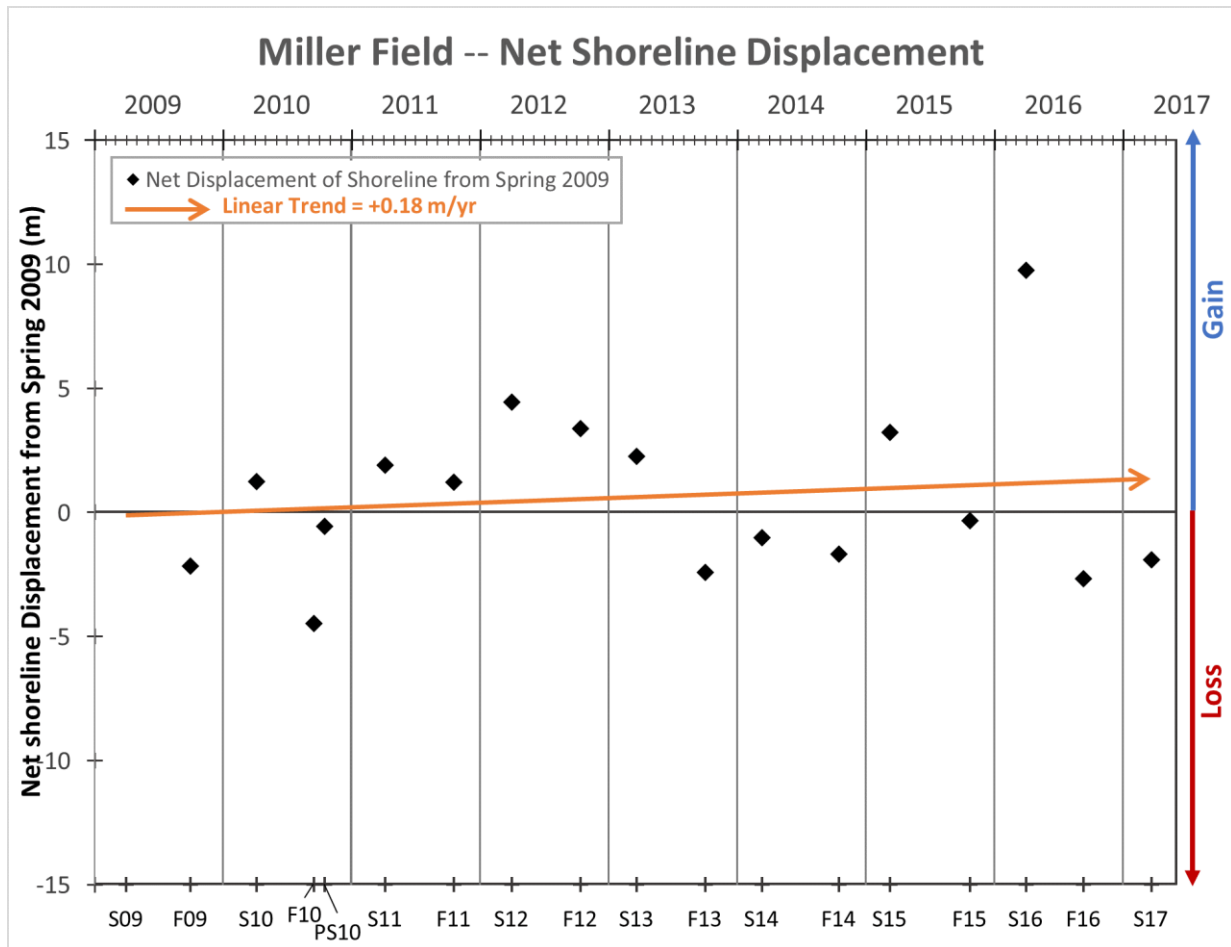


Figure 31. Trend of mean seasonal shoreline net displacement at Miller Field, Gateway National Recreation Area, Spring 2009 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Fort Wadsworth

Fort Wadsworth is located along the easternmost portion of Staten Island and is relatively sheltered from direct ocean wave exposure in Lower Bay. Fort Wadsworth is influenced by a wooden groin located near its southwestern margin and a concrete rubble structure along the northeastern 100 m adjacent to a large stone jetty (Figure 32). There is a sandy beach seaward of some of the rubble. The dominant direction of sediment transport at Miller Field varies between northeasterly or southwesterly.

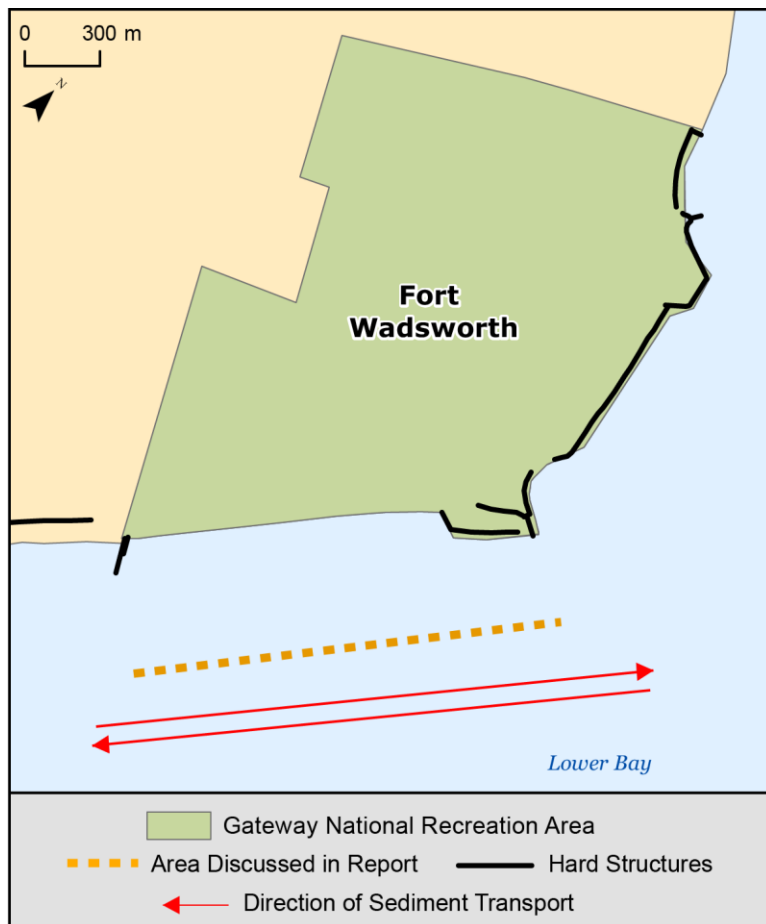


Figure 32. Features and descriptive characteristics of the Fort Wadsworth survey site, Staten Island Unit, Gateway National Recreation Area.

Annual Shoreline Change

The shoreline at Fort Wadsworth was affected by relative storminess (Figure 2) and strongly affected by the direction of alongshore transport because of structures to the northeastern and southwest (Figure 32). The several years of survey comparisons showed opposing results because dominant sediment transport direction changed. Dominant sediment transport was directed southwesterly in Spring 2012 – Spring 2013 and Spring 2013 – Spring 2014. In the Spring 2012 – Spring 2013 comparison, there were displacements ranging from +3 m seaward to -5 m landward, from southwest to northeast (Figure 33). The Spring 2013 – Spring 2014 comparison had landward displacement with landward displacements between -0.5 m and -5 m. In the two succeeding comparisons, all displacements were seaward associated with a northeasterly dominant sediment transport direction interacting with available sediment from south of Fort Wadsworth. The Spring 2014 – Spring 2015 and Spring 2015 – Spring 2016 comparisons had modest accretions of +1 m to +7 m. The Spring 2015 – Spring 2016 had slightly more seaward displacement than the Spring 2014 – Spring 2015 comparison, with a mean displacement of +4.51 m, due to increased storminess during the survey period. During the Spring 2016 – Spring 2017 comparison, the dominant sediment transport direction was to the southwest. With no sediment source to the north, the southwesterly sediment transport

caused nearly uniform landward displacement along the Fort Wadsworth shoreline, a mean of -9.71 m of landward displacement (Figure 33).

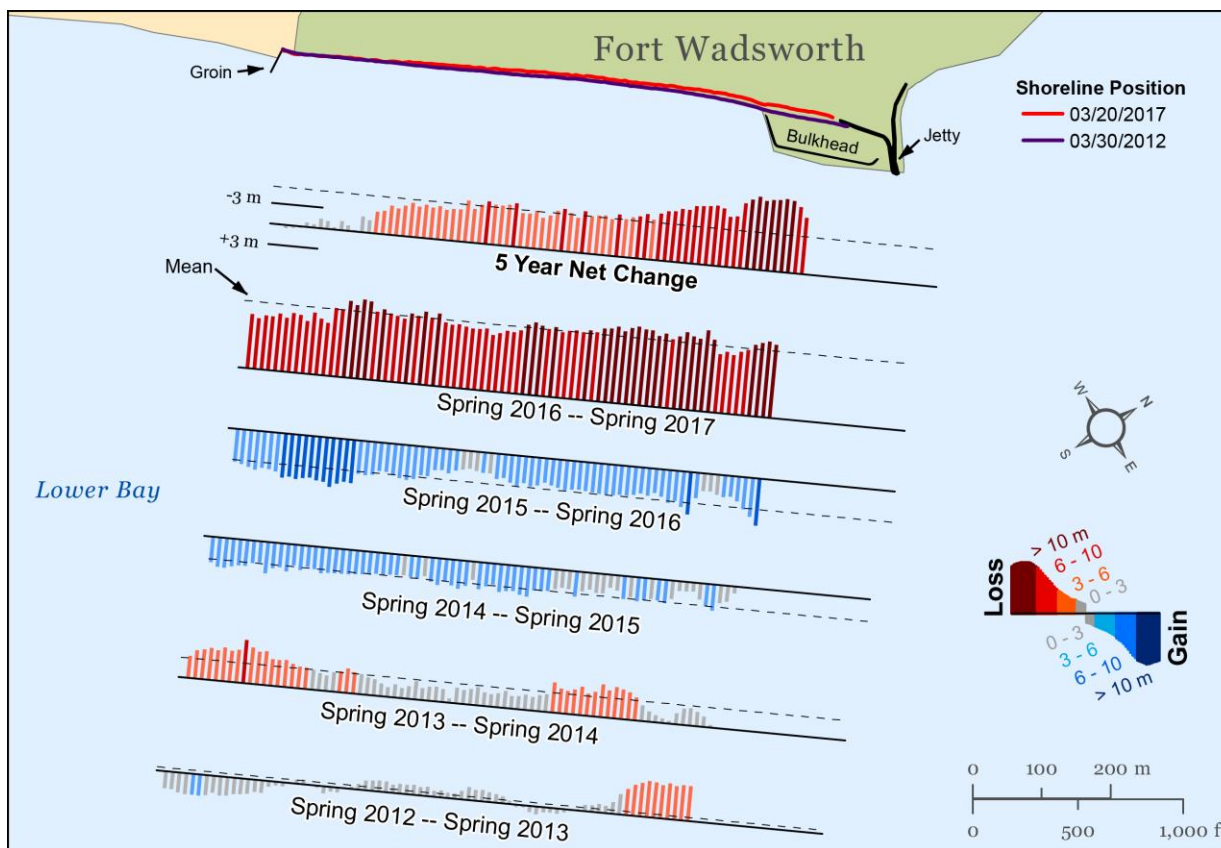


Figure 33. Distribution of annual and 5-year shoreline change at Fort Wadsworth, Gateway National Recreation Area. The scale for all vectors of change is incorporated on the 5-year net change comparison.

5-Year Shoreline Change

Nearly the entire Fort Wadsworth shoreline had landward displacement, increasing in magnitude from southwest to northeast (Figure 33). The mean change of the shoreline over the 5-year period was -5.41 m. The northern portion of Fort Wadsworth had the greatest displacement due to more years with a southwestward dominant transport direction limiting sediment input on the southwest side of the jetty. The northeastern 100 meters of beach along Fort Wadsworth had the most change over the 5-year period, a mean landward displacement of -9.96 m. Conversely, the most southwestward 100 meters of Fort Wadsworth was relatively stable over the 5-year period with landward displacements ranging from about -0.5 m to -3 m and a mean displacement of -0.58 m (Figure 33). The groin in the southwest may have helped trap some sediment, albeit having a net loss. A histogram of the distribution of dimensions of change had a trimodal characteristic (Figure 34). The greatest peak, from -5 m to -6 m, greater than the ± 3 m of uncertainty, represented the majority of vectors of change in the central portion of the Fort Wadsworth shoreline. A lesser peak from -10 to -11 represented the maximum landward displacement in the northeast and the

smallest peak from 0 m to -1 m, within the uncertainty, represented the southeastward portion of the shoreline near the groin (Figure 34).

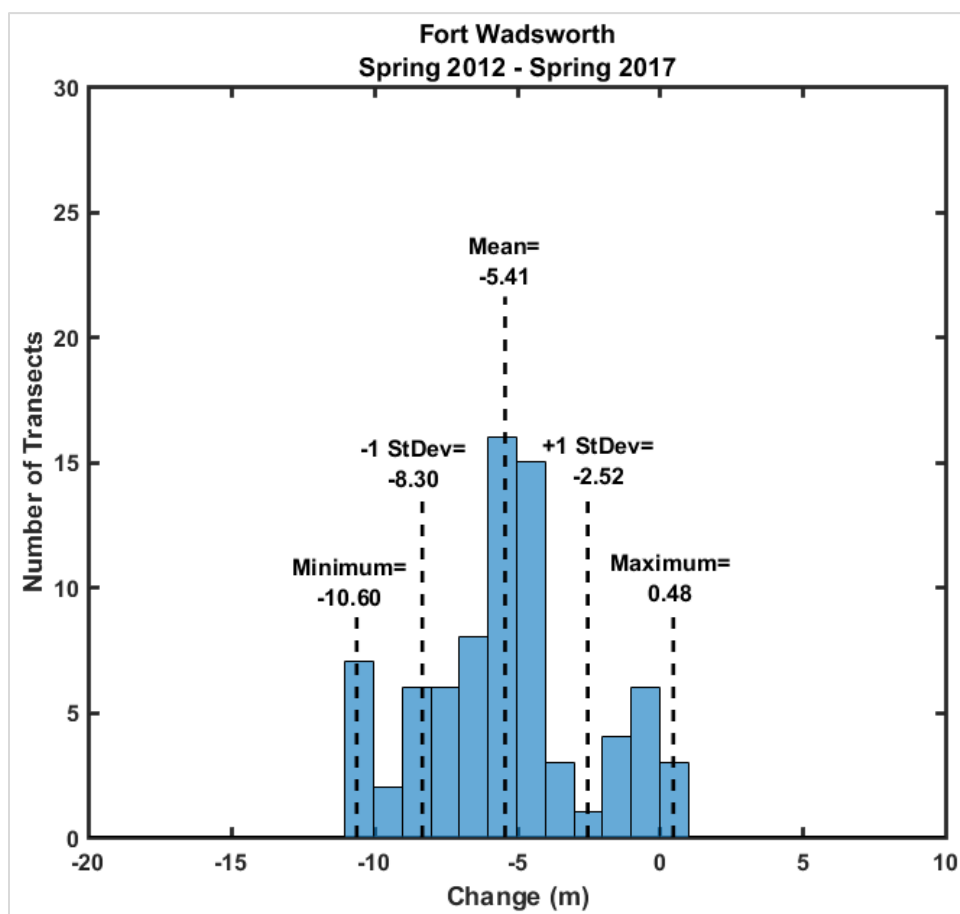


Figure 34. Histogram of vectors of shoreline change, 5-year trend from Spring 2012 to Spring 2017 at Fort Wadsworth, Gateway National Recreation Area.

Summary Statistics Tables and Trends of Change

The Fort Wadsworth data are assembled to represent seasonal, annual, and 5-year metrics of shoreline change (Table 11). Each temporal span is represented by a mean value, the standard deviation, and the maximum and minimum displacements. The seasonal mean metrics varied from -8.93 m of landward displacement (Spring 2016 – Fall 2016) to +7.10 m of seaward displacement (Fall 2014 – Spring 2015). Similarly the annual mean metrics varied from -9.71 m of landward displacement (Spring 2016 – Spring 2017) to +4.51 m of seaward displacement (Spring 2015 – Spring 2016) (Table 11).

Table 11. Seasonal, annual, and 5-year metrics of shoreline change for Fort Wadsworth, Gateway National Recreation Area, 2012 – 2017.

Temporal Period	Time Period	Mean (m)	Mean Net Displacement of Shoreline from Spring 2012	1 StDEV	Max Seaward Displacement	Max Landward Displacement
Seasonal	Spring 2012 - Fall 2012	0.90	0.90	1.80	4.98	-1.91
	Fall 2012 - Spring 2013	-1.45	-0.55	3.79	4.86	-10.10
	Spring 2013 - Fall 2013	-5.08	-5.63	1.79	–	-7.46
	Fall 2013 - Spring 2014	2.18	-3.45	1.18	4.17	-1.16
	Spring 2014 - Fall 2014	-3.86	-7.30	1.01	–	-6.49
	Fall 2014 - Spring 2015	7.10	-0.21	0.92	8.71	–
	Spring 2015 - Fall 2015	-1.51	-1.72	0.83	0.30	-2.92
	Fall 2015 - Spring 2016	6.02	4.30	0.64	7.70	–
	Spring 2016 - Fall 2016	-8.93	-4.62	1.21	–	-12.04
	Fall 2016 - Spring 2017	-0.79	-5.41	1.24	2.31	-3.69
Annual	Spring 2012 - Spring 2013	-0.55	-0.55	2.23	3.03	-5.30
	Spring 2013 - Spring 2014	-2.90	-3.45	1.24	–	-6.24
	Spring 2014 - Spring 2015	3.24	-0.21	0.70	4.56	–
	Spring 2015 - Spring 2016	4.51	4.30	1.15	7.13	–
	Spring 2016 - Spring 2017	-9.71	-5.41	1.08	–	-11.77
Net	Spring 2012 - Spring 2017	-5.41	-5.41	2.89	0.48	-10.60

The net shoreline displacement starting with the Spring 2012 survey was also calculated for each successive seasonal, annual, and 5-year temporal span. Net shoreline displacement is an additive statistical value that can display general trends of shoreline fluctuation and recovery. It is calculated by adding the mean value of annual (seasonal) shoreline change to the previous year's (season's) displacement.

Trends of the changes, expressed as a general rate of change per year, albeit not a predictive value, were determined through the application of linear regression analysis for the entire available dataset, from the initial survey in Spring 2009 to the Spring 2017 survey (Figure 35). To best understand the effects of shoreline displacement and recovery on the overall linear trend, seasonal displacement values were selected over annual displacement values because they encompassed each of the net stormy and non-stormy seasons and provide greater detail. This analysis indicates that the mean shoreline position at Fort Wadsworth was displaced seaward at the rate of +0.26 m/yr (Figure 35). The dominant sediment transport direction switching affected the trend of the shoreline and is the cause of some of the increased difference between the net displacement points the linear regression line. The larger difference between the net displacement point and the linear regression line in Post-Storm 2012, Fall 2011, and Spring 2016 was a function of storm events affecting the natural trend of the shoreline displacement (Figure 35). From Spring 2009 to Spring 2012 the net displacement rate was seaward at a rate of +2.31 m/yr and from Spring 2012 to Spring 2017 the net displacement rate was landward at a rate of -0.41m/yr.

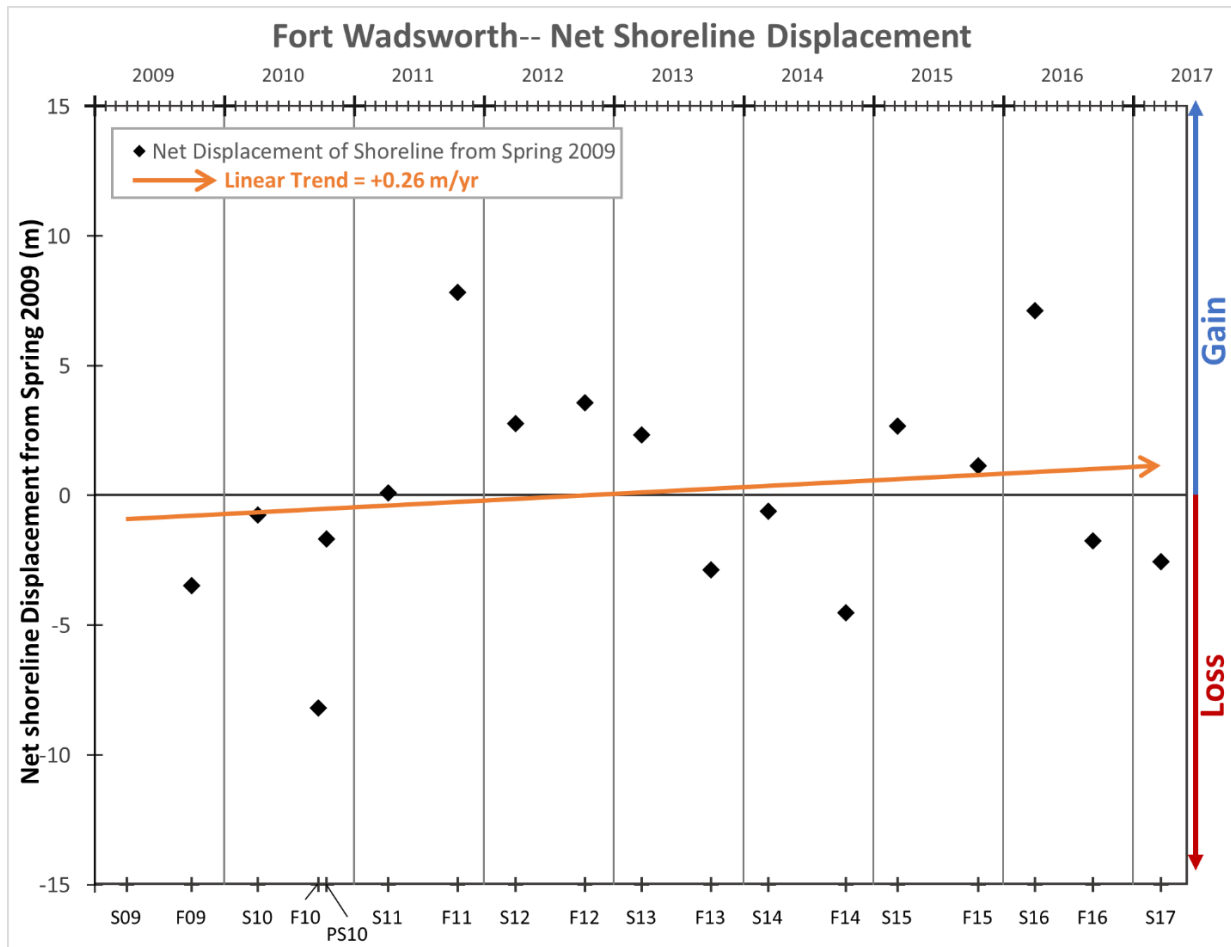


Figure 35. Trend of mean seasonal shoreline net displacement at Fort Wadsworth, Gateway National Recreation Area, Spring 2009 – Spring 2017. Seasonal survey dates are represented on the lower x-axis, and the annual timeline on the upper x-axis.

Coastal Profile Surveys (2D)

Defining Profile Features and Datums

The dune/beach profiles are surveyed and recorded relative to a fixed datum, the North American Vertical Datum of 1988 (NAVD88). At the present time, NAVD88 and mean sea level are at similar elevations (7.3 cm offset) and the dune/beach topography has a similar relationship to these two elevations (Figure 3). Referencing a constant elevation and position with a fixed monument permits the precise monitoring of spatial and elevation evolution as the profile responds to changes in sediment supply, seasonal storminess, and increased water level due to sea level rise.

Several metrics are tracked on each profile: distance to NAVD88 intercept, distance to foredune crest, foredune crest elevation, and cross-section area. Distance to NAVD88 is defined as the distance from the benchmark point to the intersection with 0 m NAVD88. The foredune crest is the most seaward, highest point in elevation within the foredune feature. Cross-section area metrics are divided into two feature categories: dune and beach. The dune-beach elevation threshold divides the two feature areas. The base of the dune is determined to be a site-specific elevation relative to NAVD88 through an analysis of the topographic profiles of the site. Cross-section area change occurring above this dune-beach threshold are considered change in the dune feature, whereas elevation and area change below the threshold and above 0 m NAVD88 are considered change in the beach feature.

Timing of Coastal Topography Surveys

Coastal topography profiles were collected within GATE semi-annually, timing and tide of survey dates were recorded (Table 12). The surveys were conducted during spring tide conditions to expose as much of the beach profile as possible and to facilitate the collection of the profile to at least the NAVD88 datum position (near mean sea level). On the basis of the protocol, the surveys occur at the end of the winter stormy period and at the end of the summer calm period, recording the seasonal variation of the dune/beach geomorphological system.

Table 12. Date of coastal topography survey and elevation of spring low tide, 2012 – 2017.

Season	Park	Date of survey	Previous High Tide	
			Height* (m)	Time
Spring 2012	Sandy Hook	03/22/2012	-0.085	1:42 PM
	Breezy Point	04/04/2012	-0.135	8:54 AM
	Plumb Beach	05/04/2012	0.170	11:47 AM
	Great Kills	05/21/2012	-0.213	1:18 PM
	Miller Field	05/21/2012	-0.213	1:18 PM
	Fort Wadsworth	05/21/2012	-0.213	1:18 PM
Spring 2013	Sandy Hook	04/05/2013	0.025	9:53 AM
	Breezy Point	–	–	–
	Plumb Beach	04/10/2013	0.034	1:37 AM
	Great Kills	04/08/2013	-0.153	12:19 PM
	Miller Field	05/30/2013	-0.105	6:00 AM
	Fort Wadsworth	05/26/2013	-0.411	2:32 AM
Spring 2014	Sandy Hook	03/17/2014	0.034	2:24 PM
	Breezy Point	03/11/2014	0.367	10:25 PM
	Plumb Beach	04/11/2014	0.043	11:09 AM
	Great Kills	05/13/2014	1.460	12:30 AM
	Miller Field	04/11/2014	0.043	11:09 AM
	Fort Wadsworth	04/11/2014	0.043	11:09 AM
Spring 2015	Sandy Hook	04/15/2015	-0.138	10:52 AM
	Breezy Point	04/16/2015	-0.262	11:43 AM
	Plumb Beach	04/23/2015	0.041	5:18 AM
	Great Kills	03/18/2015	-0.494	12:10 PM
	Miller Field	03/25/2015	-0.012	5:43 AM
	Fort Wadsworth	03/25/2015	-0.012	5:43 AM
Spring 2016	Sandy Hook	03/08/2016	-0.084	11:54 PM
	Breezy Point	03/16/2016	0.316	8:00 AM
	Plumb Beach	04/08/2016	-0.081	2:12 AM
	Great Kills	04/06/2016	-0.026	12:24 AM
	Miller Field	04/14/2016	0.110	7:42 AM
	Fort Wadsworth	04/14/2016	0.110	7:42 AM
Spring 2017	Sandy Hook	03/09/2017	-0.273	11:54 AM
	Breezy Point	03/29/2017	-0.112	2:42 PM
	Plumb Beach	03/23/2017	0.100	10:06 AM
	Great Kills	03/23/2017	0.100	10:06 AM
	Miller Field	03/23/2017	0.100	10:06 AM
	Fort Wadsworth	03/23/2017	0.100	10:06 AM

* Tide elevation values are referenced to Mean Lower Low Water (MLLW). Source: NOAA tide gauge (#8531680) Sandy Hook, New Jersey.

Uncertainty: Profile Distance, Elevation, and Cross-section Area

A calculation for profile uncertainty was developed for the 2016-2017 1D and 2D annual report (Psuty et al. 2017a). Point collection is subject to the collecting instrument's horizontal uncertainty of ± 0.02 m; this uncertainty in turn impacts all linear distance metrics (distance to NAVD88/ distance to foredune crest). A vertical uncertainty of ± 0.04 m is also incurred by point collection, and this uncertainty affects all vertical distance metrics (profile elevation). This vertical uncertainty then translates to a cross-section area uncertainty of ± 0.04 m² for every meter a profile extends (to NAVD88), applying to dune cross-section area (profile extent that exceeds dune threshold), beach cross-section area (extent below dune threshold), and total cross-section area (Psuty et al. 2012). A comparison of two metrics will have an uncertainty equivalent to the square root of the sum of squares of each survey's individual error. These sources of uncertainty were incorporated into all tables. Profiles SH9.1 and SH9.2 were not present until post-Hurricane Sandy, and thus LiDAR was used to supplement data and derive metrics of a pre-storm condition. LiDAR data inherently has a higher horizontal and vertical uncertainty. The 2010 Lidar dataset has a horizontal uncertainty of ± 0.75 m and a vertical uncertainty of ± 0.2 m and is used as the initial pre-storm dataset in Profiles SH9.1 and SH9.2 (Figure 41 and Figure 42); thus, elevation and cross-section area uncertainty for these profiles are ± 0.2 m and ± 0.2 m², respectively (USACE 2010).

Coastal Topography Metrics of Change

Sandy Hook Unit

Sandy Hook is a spit extending into New York Harbor. Along the oceanside the sediment transport direction is from south to north, and from north to south along the bayside. There is a continuous foredune feature along the oceanside and northern tip of Sandy Hook. The bayside has considerably more hard structures, with smaller discontinuous foredunes. A detailed report of the geomorphology of Sandy Hook is available (Psuty et al. 2015a; Psuty et al. 2017b). There are several communities south of Sandy Hook that placed sand on beaches during the survey period. Beach nourishment occurred in 2012, 2013, and 2014 with a total of 6,500,000 yds³ (5,000,000 m³) placed updrift of Sandy Hook (Table 2). There was also dredging of the federal channel directly north of Sandy Hook in 2012, 2013, and 2015. The effects of dredging on the 2D profiles were twofold: during dredging portions of the northern tip of Sandy Hook were closed causing some data gaps in the northern tip profiles, and dredging removed sediment from the system, potentially leading to erosion of the profiles. The dredged navigation channel is so close to the northern tip of Sandy Hook that during the 2012 dredging a portion of the beach near the accreting node sloughed off into the channel due to the dredging. Because of this loss in the beach, the initial location of benchmark SH9 was lost, and it was relocated inland.

Sixteen transects have been established along the ocean and bay shoreline of Sandy Hook (Figure 36). Each transect is tied to a stable benchmark or "monument" that is associated with some pre-existing item, such as a concrete pad, or tied to a newly-installed PVC pipe filled with and embedded in concrete. The location, description, and coordinates of the Sandy Hook monuments are detailed in a booklet prepared for this purpose (Psuty et al. 2010g).



Figure 36. Sites of coastal topography profiles on the Sandy Hook Unit of Gateway National Recreation Area.

The benchmark and Profiles 9.1 and 9.2 were moved in Fall 2013, so profiles are not comparable to previous reports. An initial profile was derived from 2010 LiDAR data, shown in grey, with the caveat that LiDAR-derived profile data have greater uncertainty than field survey data (USACE 2010). In spring 2012, Profiles SH10, SH11, and SH12 were not collected due to dredging at the northern tip of Sandy Hook. As a result, the Spring 2011 survey was used as the initial survey. During the Spring 2015 survey, profiles SH1 and SH2 were closed off due to plover fencing, and data could not be collected. The Fall 2015 survey was used instead.

Annual Topography Change

Topography at Sandy Hook can be split into three sections: oceanside (SH1 – SH9.1), northern tip (SH9.2 – SH12) and bayside (SH13 – SH16). Along Sandy Hook Oceanside, Profiles SH1 - SH6 were largely impacted by Hurricane Sandy in October 2012 (Figure 37 –Figure 39; Table 13). The foredune along the profiles was eliminated and the new foredune crest in Spring 2013 was located -5 to -45 m inland of the pre-storm location. There was also loss low on the beach feature along all of these profiles immediately post-storm that has continued for the most part through the most recent survey. Higher on the beach feature in the berm and in the dune feature Profiles SH1 - SH4 gained area. To the north, Profiles SH7 and SH8 were generally more stable with a wider and higher beach feature and higher dune feature (Figure 40; Table 13). The foredune along Profiles SH7 and SH8 was not eliminated during Hurricane Sandy. Post-storm, the dune feature continued to be stable through the 2017 survey. The beach feature gained area low on the profile. This gain in the beach feature may be due to the change in orientation of the shoreline, and nourishment episodes in communities to the south. Profile 9.1, the northernmost oceanside profile of Sandy Hook, was eroded based on the topography derived from the 2010 LiDAR compared to the Spring 2013 survey (Figure 41; Table 13). This erosion may be due not only to Hurricane Sandy but also because of the dredging of the Sandy Hook Navigation Channel directly to the north of Sandy Hook that removed sediment from the system. The dredging caused a portion of the beach to slough off and displaced the tip of the accreting node at Sandy Hook.

The two profiles on the eastern half of the northern tip of Sandy Hook (SH9.2 and SH10) gained cross-section area in the beach and dune features annually from the initial survey to the Spring 2017 survey (Figure 42; Table 13). The dune feature was relatively stable in both profiles. To the west, the foredune was eliminated along SH11 and erosion persisted in both the beach and dune feature. In the Spring 2017 survey, a scarp was present in Profile SH11 (Figure 43; Table 13). Profile SH12 was eroded from 2011 – 2013 and has been relatively stable post-storm.

The bayside profiles were all more stable than the oceanside or northern tip profiles (Figure 44 and Figure 45; Table 13). In general, these profiles had some gain in the dune feature, with a stable foredune crest position. Change in the beach feature was variable annually. SH16, however, constantly eroded in both the beach and dune feature. Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest, and cross section area at Sandy Hook Unit are found in Table 13.

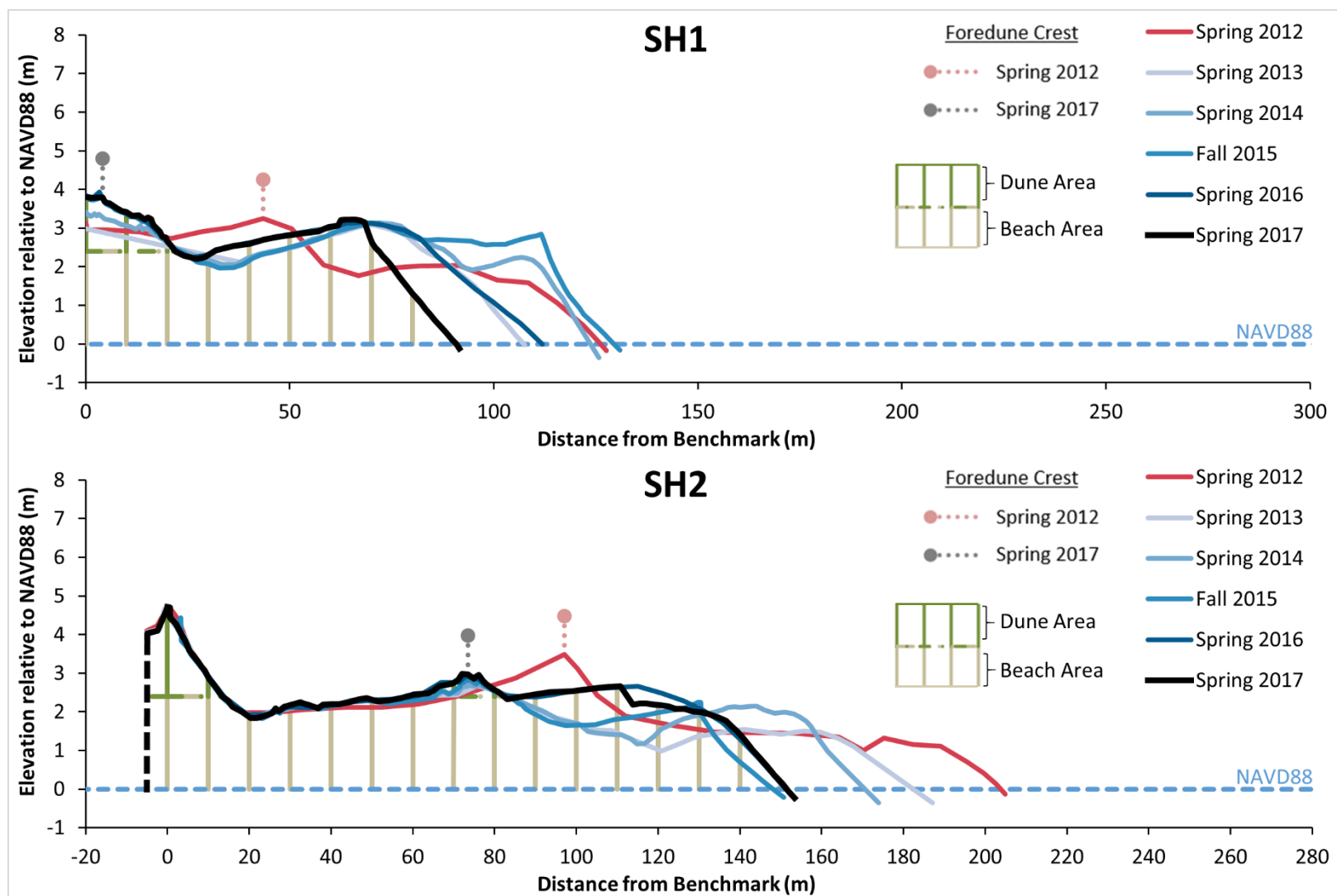


Figure 37. Coastal topography of Profiles SH1 and SH2 along the oceanside of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dotted line, color coded respectively.

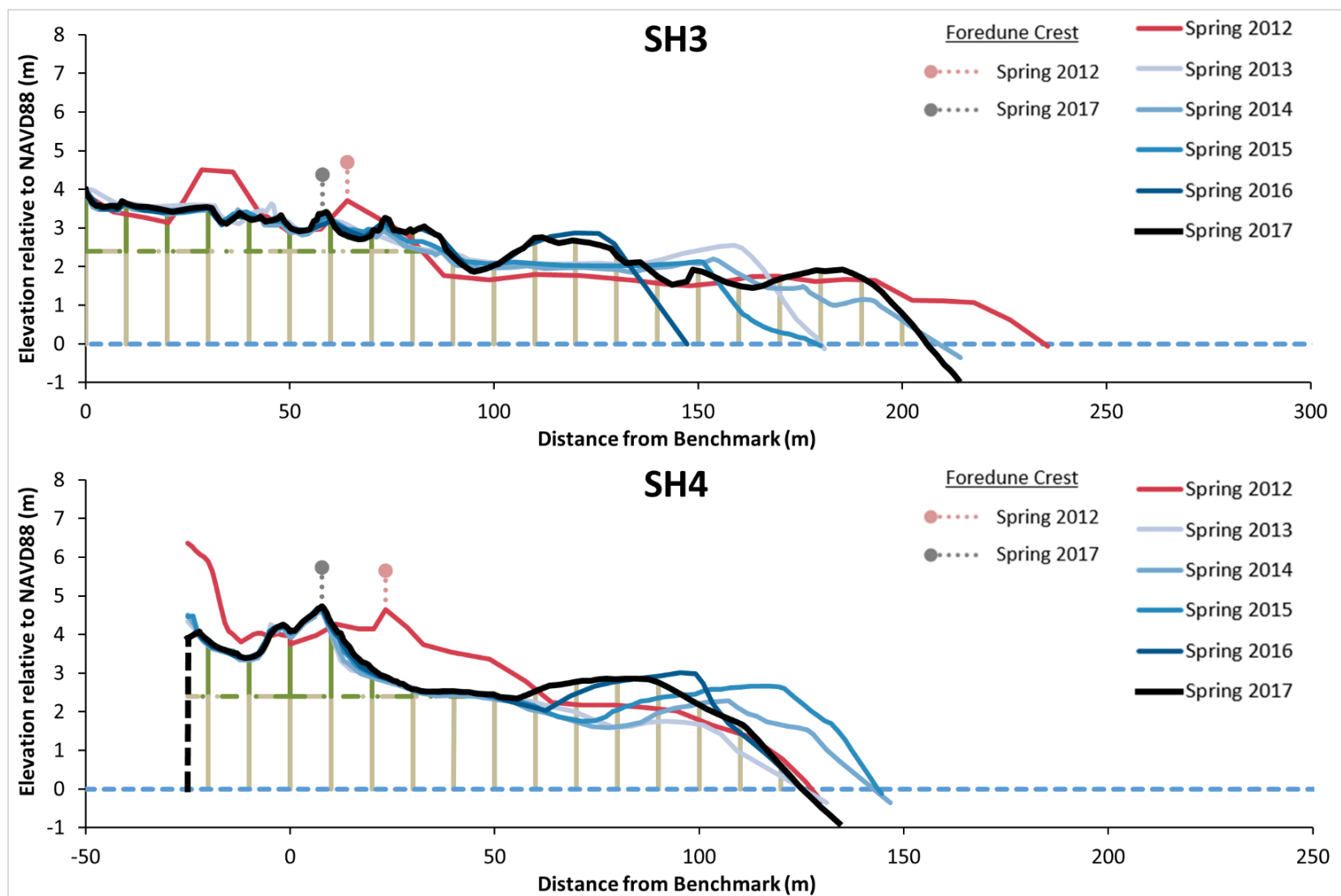


Figure 38. Coastal topography of Profiles SH3 and SH4 along the oceanside of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

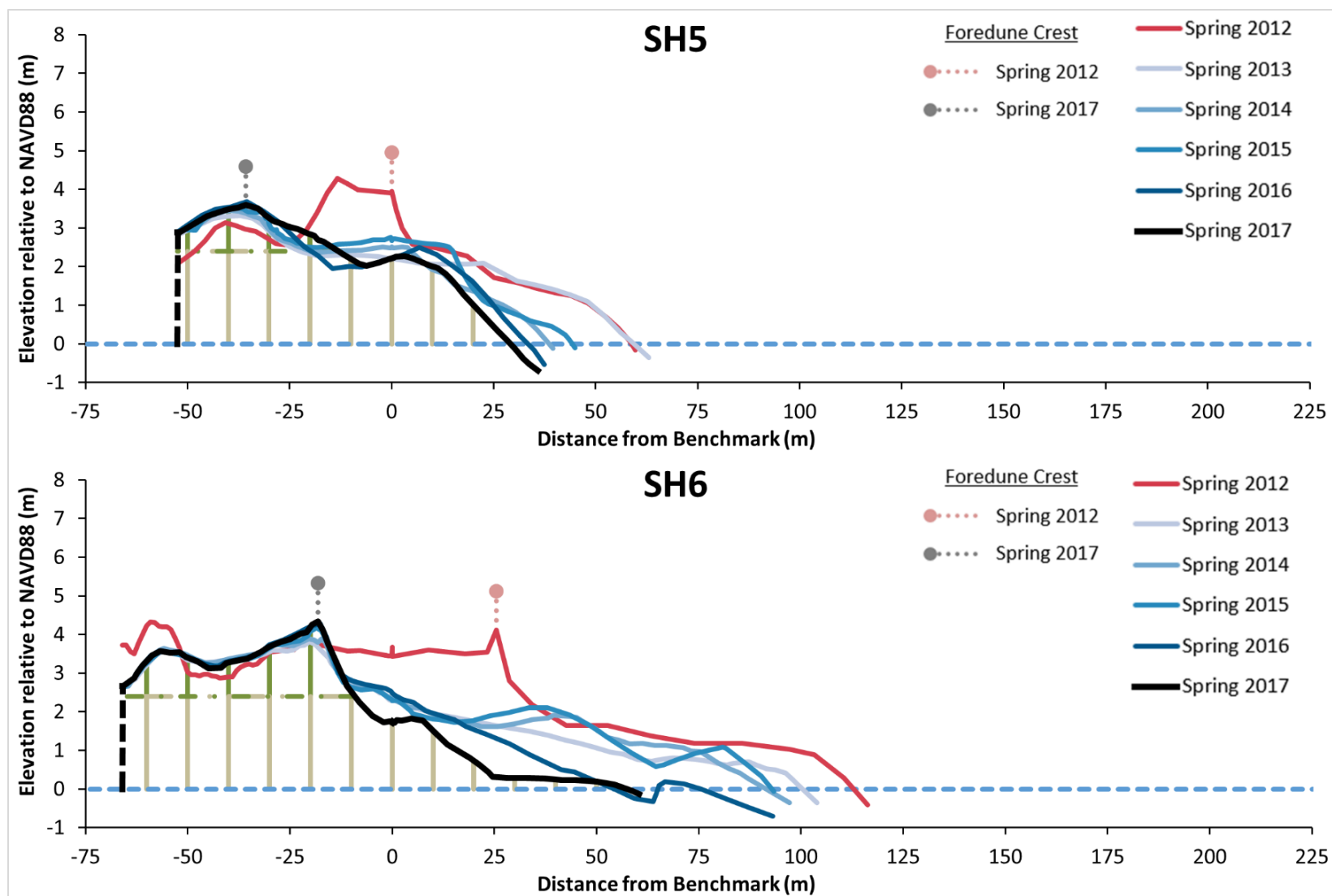


Figure 39. Coastal topography of Profiles SH5 and SH6 along the oceanside of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

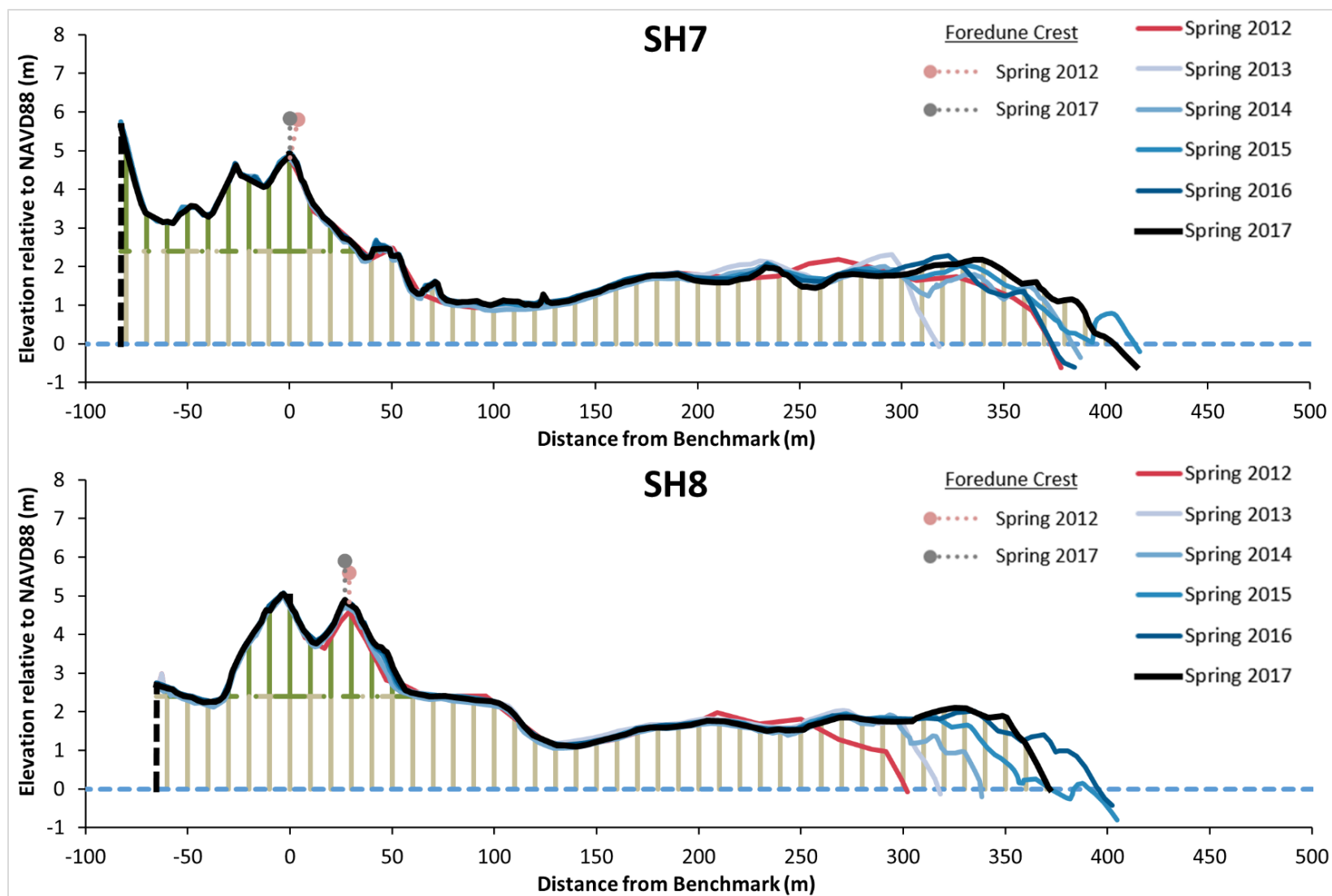


Figure 40. Coastal topography of Profiles SH7 and SH8 along the oceanside of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

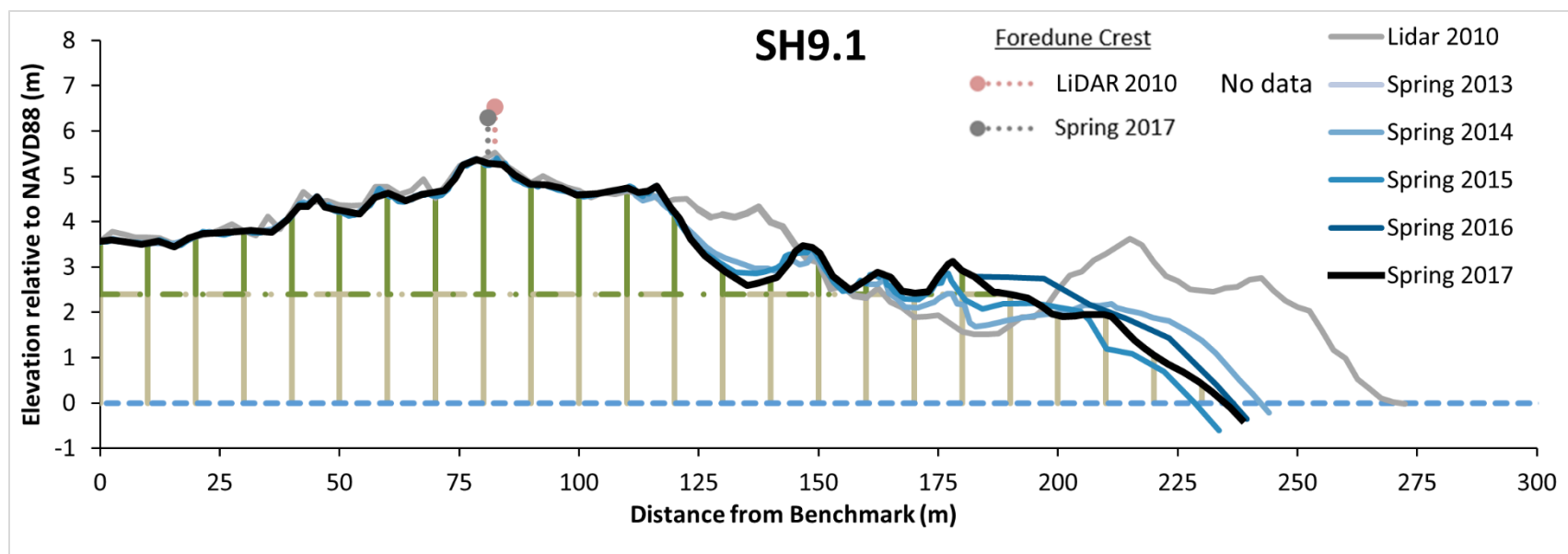


Figure 41. Coastal topography of Profiles SH9.1 along the oceanside of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

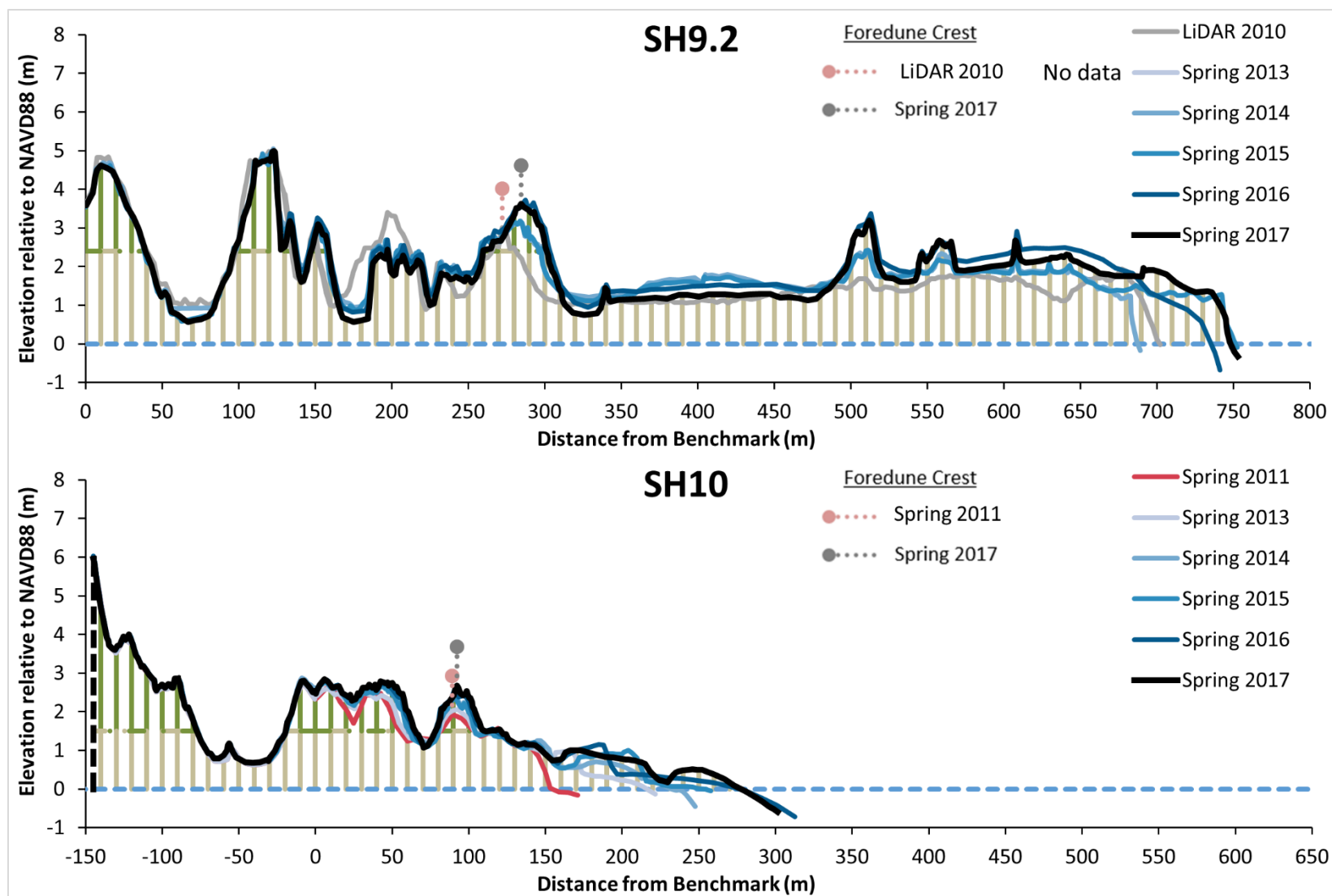


Figure 42. Coastal topography of Profiles SH9.2 and SH10 along the northern tip of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

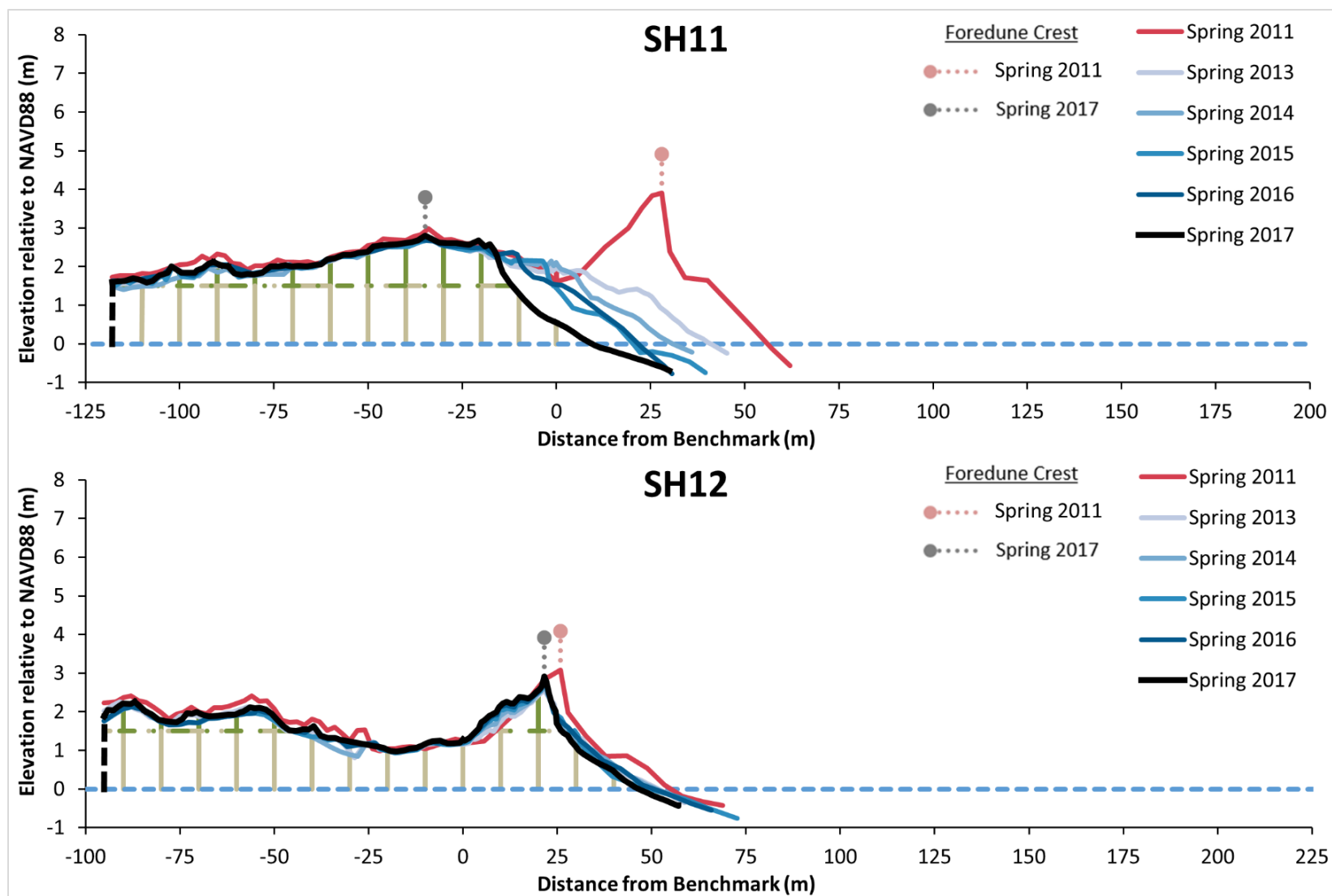


Figure 43. Coastal topography of Profiles SH11 and SH12 along the northern tip of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

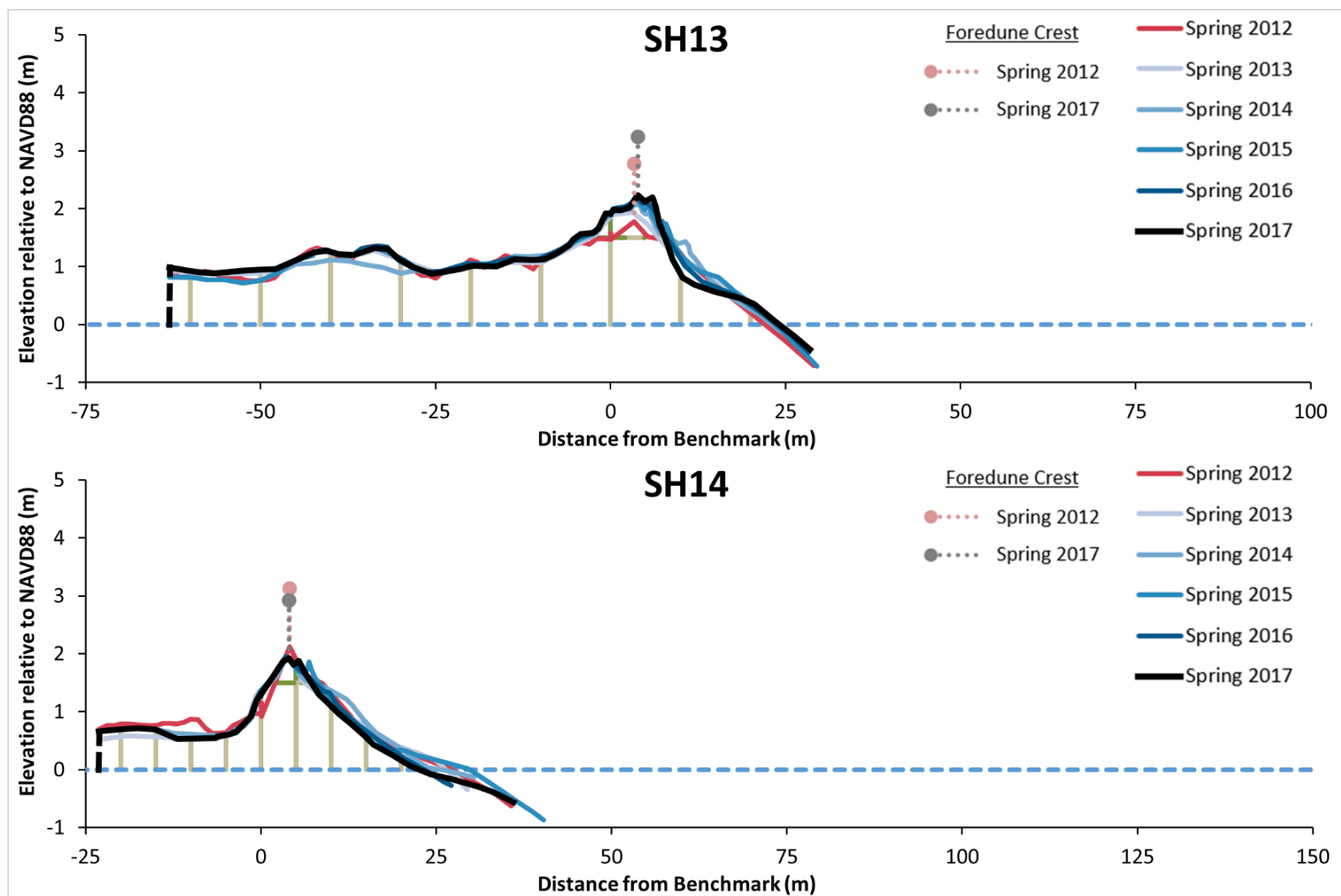


Figure 44. Coastal topography of Profiles SH13 and SH14 along the bayside of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

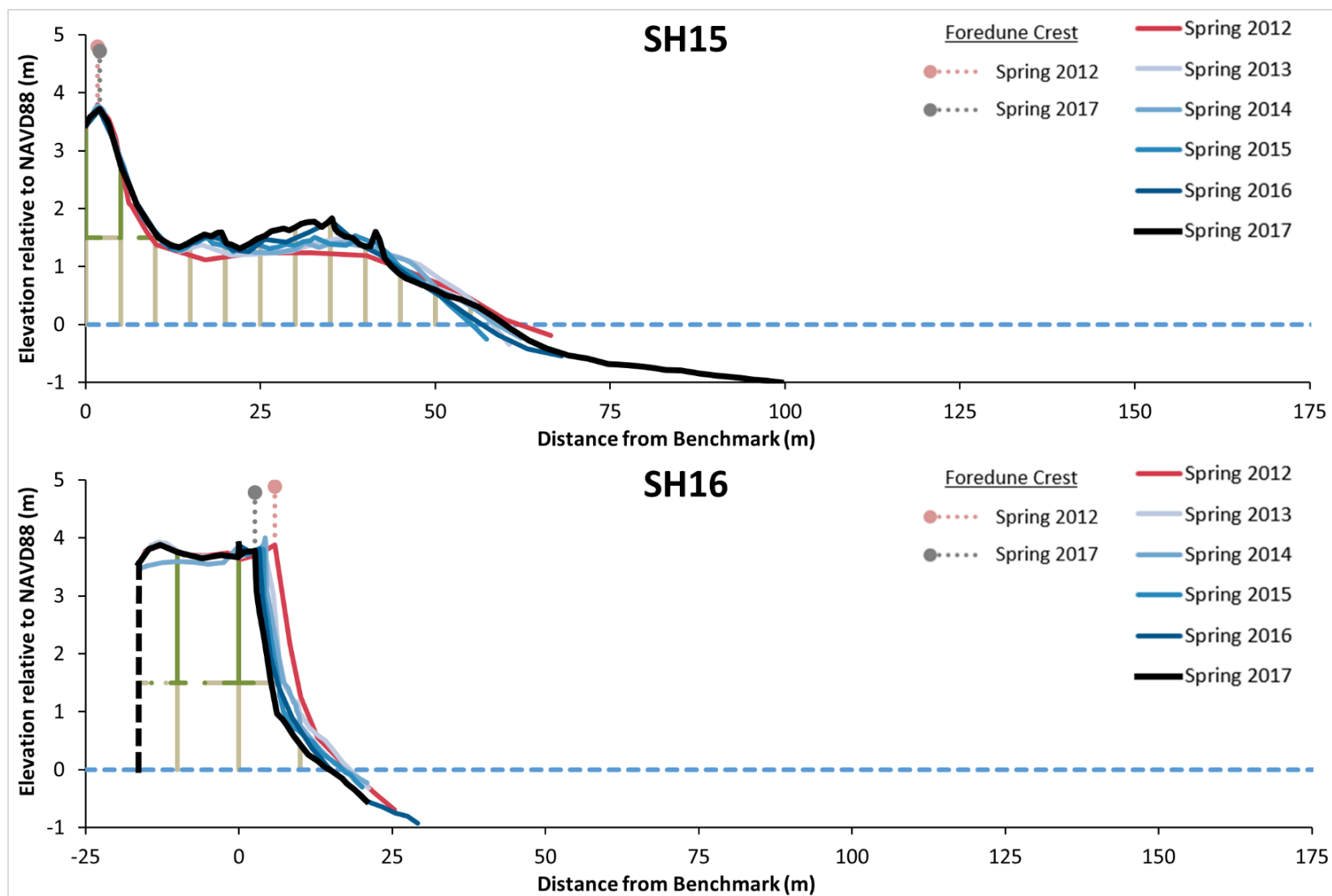


Figure 45. Coastal topography of Profiles SH15 and SH16 along the bayside of the Sandy Hook Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

Table13. Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Sandy Hook Unit, Gateway National Recreation Area. Data gaps due to missing profiles during a survey season are noted as –.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012- Spring 2013	SH1	-18.78 ± 0.03	-43.46 ± 0.03	-0.27 ± 0.06	-27.83 ± 6.63	-22.27 ± 2.43	-5.57 ± 4.33
	SH2	-21.25 ± 0.03	-21.19 ± 0.03	-0.80 ± 0.06	-62.14 ± 11.22	-16.13 ± 2.64	-46.01 ± 8.60
	SH3	-54.71 ± 0.03	-4.97 ± 0.03	-0.47 ± 0.06	-46.35 ± 11.83	-15.05 ± 4.80	-31.29 ± 7.14
	SH4	-2.06 ± 0.03	-15.17 ± 0.03	-0.03 ± 0.06	-91.21 ± 8.56	-68.21 ± 4.64	-23.00 ± 3.94
	SH5	0.48 ± 0.03	-36.93 ± 0.03	-0.64 ± 0.06	-33.48 ± 6.31	-28.22 ± 2.76	-5.26 ± 3.82
	SH6	-12.47 ± 0.03	-45.67 ± 0.03	-0.31 ± 0.06	-115.47 ± 9.77	-51.90 ± 4.70	-63.56 ± 5.20
	SH7	-55.75 ± 0.03	0.23 ± 0.03	-0.02 ± 0.06	-72.37 ± 24.27	1.22 ± 7.03	-73.59 ± 17.27
	SH8	15.96 ± 0.03	-1.94 ± 0.03	0.32 ± 0.06	59.81 ± 21.21	8.97 ± 7.25	50.84 ± 13.97
	SH9.1*	–	–	–	–	–	–
	SH9.2*	–	–	–	–	–	–
	SH10	61.79 ± 0.03	3.80 ± 0.03	0.12 ± 0.06	42.94 ± 18.76	10.56 ± 9.54	32.38 ± 9.30
	SH11	-15.14 ± 0.03	-63.13 ± 0.03	-1.15 ± 0.06	-82.74 ± 9.43	-54.15 ± 8.25	-28.59 ± 1.27
	SH12	-3.34 ± 0.03	-3.96 ± 0.03	-0.49 ± 0.06	-30.82 ± 8.40	-18.84 ± 4.52	-11.99 ± 3.93
	SH13	1.52 ± 0.03	-0.22 ± 0.03	0.16 ± 0.06	3.70 ± 4.86	1.97 ± 0.46	1.73 ± 4.41
	SH14	-0.84 ± 0.03	-0.49 ± 0.03	-0.20 ± 0.06	-4.21 ± 2.82	-0.56 ± 0.33	-3.65 ± 2.50
	SH15	-3.89 ± 0.03	-0.16 ± 0.03	-0.03 ± 0.06	5.23 ± 3.40	0.81 ± 0.57	4.41 ± 2.84
	SH16	0.16 ± 0.03	-1.50 ± 0.03	0.06 ± 0.06	-4.71 ± 1.95	-3.90 ± 1.41	-0.81 ± 0.54
Spring 2013- Spring 2014	SH1	16.35 ± 0.03	0.00 ± 0.03	0.43 ± 0.06	+49.40 ± 6.55	+6.39 ± 1.40	+43.01 ± 5.16
	SH2	-11.91 ± 0.03	0.25 ± 0.03	0.02 ± 0.06	+9.25 ± 10.27	+0.42 ± 2.19	+8.83 ± 8.08
	SH3	28.82 ± 0.03	0.02 ± 0.03	-0.01 ± 0.06	+3.64 ± 11.03	-8.91 ± 4.82	+12.54 ± 6.25
	SH4	17.28 ± 0.03	-0.91 ± 0.03	-0.02 ± 0.06	+37.37 ± 9.01	-3.88 ± 4.14	+41.25 ± 4.91
	SH5	-20.65 ± 0.03	-2.43 ± 0.03	0.13 ± 0.06	-32.92 ± 5.77	+3.33 ± 2.34	-36.25 ± 3.65
	SH6	-8.93 ± 0.03	-0.15 ± 0.03	0.09 ± 0.06	+15.39 ± 9.16	+4.22 ± 3.65	+11.17 ± 5.51
	SH7	66.00 ± 0.03	-0.28 ± 0.03	-0.02 ± 0.06	+61.58 ± 24.58	-3.14 ± 7.04	+64.72 ± 17.57
	SH8	20.60 ± 0.03	-0.36 ± 0.03	-0.09 ± 0.06	-16.85 ± 22.24	-10.78 ± 6.44	-6.07 ± 15.87
	SH9.1*	–	–	–	–	–	–

* No Spring 2012 or 2013 surveys conducted, initial profile is LiDAR 2010

** No Spring 2015 survey conducted, Fall 2015 survey used.

Table13 (continued). Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Sandy Hook Unit, Gateway National Recreation Area. Data gaps due to missing profiles during a survey season are noted as –.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2013- Spring 2014 (cont.)	SH9.2*	–	–	–	–	–	–
	SH10	15.27 \pm 0.03	-2.13 \pm 0.03	0.39 \pm 0.06	37.41 \pm 20.86	21.66 \pm 9.66	15.76 \pm 11.20
	SH11	-10.11 \pm 0.03	0.16 \pm 0.03	0.00 \pm 0.06	-21.00 \pm 8.71	-3.69 \pm 6.93	-17.31 \pm 1.80
	SH12	-0.50 \pm 0.03	-0.07 \pm 0.03	0.12 \pm 0.06	-3.76 \pm 8.29	-2.83 \pm 4.05	-0.93 \pm 4.24
	SH13	-0.48 \pm 0.03	0.33 \pm 0.03	0.13 \pm 0.06	-2.75 \pm 4.89	1.00 \pm 0.62	-3.75 \pm 4.28
	SH14	-0.89 \pm 0.03	-0.12 \pm 0.03	0.01 \pm 0.06	2.69 \pm 2.77	0.12 \pm 0.30	2.57 \pm 2.47
	SH15	0.60 \pm 0.03	0.26 \pm 0.03	0.02 \pm 0.06	-0.50 \pm 3.31	0.11 \pm 0.61	-0.61 \pm 2.70
	SH16	-0.87 \pm 0.03	-0.04 \pm 0.03	0.06 \pm 0.06	-5.06 \pm 1.93	-3.56 \pm 1.34	-1.50 \pm 0.58
Spring 2014- Spring 2015	SH1**	5.72 \pm 0.03	3.85 \pm 0.03	0.38 \pm 0.06	24.02 \pm 7.16	5.37 \pm 1.33	18.65 \pm 5.83
	SH2**	-22.40 \pm 0.03	0.20 \pm 0.03	0.12 \pm 0.06	-40.83 \pm 9.32	0.29 \pm 2.11	-41.12 \pm 7.21
	SH3	-29.92 \pm 0.03	-0.35 \pm 0.03	0.08 \pm 0.06	-36.77 \pm 11.00	7.24 \pm 4.83	-44.01 \pm 6.22
	SH4	1.07 \pm 0.03	-0.38 \pm 0.03	0.09 \pm 0.06	43.86 \pm 9.51	6.57 \pm 4.06	37.29 \pm 5.46
	SH5	5.64 \pm 0.03	1.68 \pm 0.03	0.07 \pm 0.06	16.98 \pm 5.31	8.51 \pm 3.36	8.47 \pm 2.01
	SH6	1.46 \pm 0.03	1.79 \pm 0.03	0.28 \pm 0.06	2.12 \pm 8.95	-1.16 \pm 3.66	3.28 \pm 5.29
	SH7	30.58 \pm 0.03	0.00 \pm 0.03	0.11 \pm 0.06	49.26 \pm 27.25	4.44 \pm 7.02	44.82 \pm 20.23
	SH8	53.23 \pm 0.03	-0.53 \pm 0.03	0.03 \pm 0.06	81.98 \pm 24.37	14.25 \pm 6.70	67.73 \pm 17.69
	SH9.1	-13.66 \pm 0.03	-0.03 \pm 0.03	-0.01 \pm 0.06	-25.74 \pm 13.33	-0.23 \pm 9.62	-25.51 \pm 3.75
	SH9.2	63.96 \pm 0.03	-0.47 \pm 0.03	-0.01 \pm 0.06	51.48 \pm 40.74	-2.93 \pm 7.92	54.41 \pm 32.83
	SH10	21.39 \pm 0.03	-0.15 \pm 0.03	-0.04 \pm 0.06	6.24 \pm 21.90	-3.39 \pm 9.78	9.63 \pm 12.13
	SH11	-10.40 \pm 0.03	1.28 \pm 0.03	-0.05 \pm 0.06	-10.92 \pm 8.13	1.49 \pm 6.53	-12.41 \pm 1.64
	SH12	-1.78 \pm 0.03	-0.13 \pm 0.03	0.08 \pm 0.06	1.17 \pm 8.23	1.91 \pm 4.13	-0.74 \pm 4.10
	SH13	0.38 \pm 0.03	0.17 \pm 0.03	0.16 \pm 0.06	3.83 \pm 4.88	0.88 \pm 0.69	2.96 \pm 4.19
	SH14	4.27 \pm 0.03	0.34 \pm 0.03	-0.02 \pm 0.06	-1.26 \pm 2.87	0.43 \pm 0.37	-1.69 \pm 2.50
	SH15	-3.64 \pm 0.03	-0.04 \pm 0.03	-0.05 \pm 0.06	-1.43 \pm 3.22	-0.32 \pm 0.60	-1.11 \pm 2.62
	SH16	-0.28 \pm 0.03	-0.33 \pm 0.03	-0.20 \pm 0.06	-0.74 \pm 1.89	0.92 \pm 1.32	-1.66 \pm 0.58

* No Spring 2012 or 2013 surveys conducted, initial profile is LiDAR 2010

** No Spring 2015 survey conducted, Fall 2015 survey used.

Table13 (continued). Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Sandy Hook Unit, Gateway National Recreation Area. Data gaps due to missing profiles during a survey season are noted as –.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2015- Spring 2016	SH1	-17.53 ± 0.03	-0.48 ± 0.03	0.14 ± 0.06	-45.41 ± 6.84	0.73 ± 1.29	-46.14 ± 5.56
	SH2	3.10 ± 0.03	-3.40 ± 0.03	0.11 ± 0.06	41.13 ± 8.75	2.69 ± 2.29	38.44 ± 6.48
	SH3	-31.74 ± 0.03	1.01 ± 0.03	-0.15 ± 0.06	-24.90 ± 9.27	0.92 ± 5.03	-25.81 ± 4.31
	SH4	-18.78 ± 0.03	-0.11 ± 0.03	-0.01 ± 0.06	-34.73 ± 9.03	-0.67 ± 4.19	-34.07 ± 4.85
	SH5	-10.85 ± 0.03	2.17 ± 0.03	0.16 ± 0.06	-17.34 ± 5.17	-2.77 ± 3.08	-14.56 ± 2.28
	SH6	-17.45 ± 0.03	0.86 ± 0.03	0.12 ± 0.06	-59.85 ± 8.51	5.20 ± 3.73	-65.05 ± 4.80
	SH7	-40.40 ± 0.03	0.03 ± 0.03	-0.01 ± 0.06	-22.44 ± 26.99	-1.86 ± 7.10	-20.57 ± 19.90
	SH8	3.98 ± 0.03	1.50 ± 0.03	0.02 ± 0.06	55.31 ± 25.94	1.89 ± 7.13	53.42 ± 18.83
	SH9.1	7.89 ± 0.03	-1.85 ± 0.03	-0.11 ± 0.06	37.60 ± 13.16	10.31 ± 10.68	27.29 ± 2.58
	SH9.2	-15.97 ± 0.03	3.31 ± 0.03	0.55 ± 0.06	88.52 ± 42.06	-13.37 ± 6.87	101.89 ± 35.30
	SH10	23.57 ± 0.03	0.39 ± 0.03	0.18 ± 0.06	25.29 ± 23.17	13.32 ± 10.25	11.97 ± 12.93
	SH11	1.34 ± 0.03	-1.93 ± 0.03	-0.03 ± 0.06	5.58 ± 7.87	1.66 ± 6.70	3.92 ± 1.17
	SH12	1.14 ± 0.03	-0.02 ± 0.03	0.06 ± 0.06	6.26 ± 8.21	1.93 ± 4.34	4.33 ± 3.87
	SH13	0.30 ± 0.03	0.08 ± 0.03	-0.01 ± 0.06	2.23 ± 4.90	0.15 ± 0.72	2.08 ± 4.19
	SH14	-6.46 ± 0.03	-0.29 ± 0.03	0.04 ± 0.06	-0.95 ± 2.81	-0.12 ± 0.39	-0.83 ± 2.42
	SH15	1.54 ± 0.03	0.21 ± 0.03	-0.03 ± 0.06	1.87 ± 3.16	0.08 ± 0.65	1.80 ± 2.52
	SH16	-1.93 ± 0.03	-0.70 ± 0.03	0.00 ± 0.06	-1.07 ± 1.83	-0.91 ± 1.28	-0.16 ± 0.55
Spring 2016- Spring 2017	SH1	-21.14 ± 0.03	0.73 ± 0.03	-0.13 ± 0.06	-48.62 ± 5.76	0.41 ± 1.26	-49.03 ± 4.51
	SH2	0.18 ± 0.03	0.56 ± 0.03	0.04 ± 0.06	-3.21 ± 8.84	0.35 ± 2.46	-3.56 ± 6.39
	SH3	58.81 ± 0.03	-1.76 ± 0.03	0.21 ± 0.06	97.99 ± 10.13	1.70 ± 5.05	96.29 ± 5.23
	SH4	0.25 ± 0.03	1.00 ± 0.03	0.05 ± 0.06	6.19 ± 8.49	2.70 ± 4.25	3.49 ± 4.24
	SH5	-4.25 ± 0.03	-0.22 ± 0.03	-0.09 ± 0.06	-7.58 ± 4.74	1.38 ± 2.16	-8.96 ± 2.58
	SH6	-18.03 ± 0.03	-0.47 ± 0.03	0.05 ± 0.06	-37.13 ± 7.51	-4.32 ± 3.52	-32.82 ± 3.99
	SH7	30.39 ± 0.03	0.03 ± 0.03	-0.03 ± 0.06	27.45 ± 26.69	-2.78 ± 7.10	30.23 ± 19.60
	SH8	-23.58 ± 0.03	-0.62 ± 0.03	0.04 ± 0.06	-27.89 ± 25.40	-0.92 ± 6.70	-26.98 ± 18.70
	SH9.1	-1.65 ± 0.03	0.00 ± 0.03	0.00 ± 0.06	-19.85 ± 13.33	-5.43 ± 11.10	-14.42 ± 2.26

* No Spring 2012 or 2013 surveys conducted, initial profile is LiDAR 2010

** No Spring 2015 survey conducted, Fall 2015 survey used.

Table13 (continued). Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Sandy Hook Unit, Gateway National Recreation Area. Data gaps due to missing profiles during a survey season are noted as —.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2016- Spring 2017 (cont.)	SH9.2	12.76 \pm 0.03	-2.66 \pm 0.03	-0.10 \pm 0.06	-80.61 \pm 41.97	20.53 \pm 6.62	-101.14 \pm 35.42
	SH10	0.90 \pm 0.03	1.41 \pm 0.03	0.09 \pm 0.06	17.30 \pm 23.86	2.71 \pm 10.81	14.59 \pm 13.05
	SH11	-12.32 \pm 0.03	0.84 \pm 0.03	0.11 \pm 0.06	-26.47 \pm 7.56	-3.72 \pm 6.41	-22.75 \pm 1.16
	SH12	-4.05 \pm 0.03	-0.11 \pm 0.03	0.05 \pm 0.06	1.78 \pm 8.13	5.12 \pm 4.46	-3.34 \pm 3.67
	SH13	0.30 \pm 0.03	0.18 \pm 0.03	0.01 \pm 0.06	-1.96 \pm 4.92	0.15 \pm 0.72	-2.11 \pm 4.20
	SH14	-0.65 \pm 0.03	0.47 \pm 0.03	-0.03 \pm 0.06	-1.70 \pm 2.61	0.06 \pm 0.39	-1.75 \pm 2.22
	SH15	3.22 \pm 0.03	0.07 \pm 0.03	0.02 \pm 0.06	3.79 \pm 3.30	0.15 \pm 0.75	3.64 \pm 2.55
	SH16	-0.25 \pm 0.03	-0.64 \pm 0.03	-0.02 \pm 0.06	-4.01 \pm 1.77	-1.81 \pm 1.25	-2.20 \pm 0.52

* No Spring 2012 or 2013 surveys conducted, initial profile is LiDAR 2010

** No Spring 2015 survey conducted, Fall 2015 survey used.

5-year Topography Change

From the initial surveys to the Spring 2017 survey, profiles along the southern portion of the oceanside lost cross-section area and the intersection with NAVD88 was displaced inland (Figure 46; Table 14). The foredune crest location was also displaced inland with variable gains and losses in elevation. The northern portion of the oceanside was more accretional with gains in cross-section area and distance to NAVD88 in profiles with a stable dune feature. Along the northern tip of Sandy Hook, Profiles SH9.2 and SH10 gained area in the beach feature and the intersection with NAVD88 was displaced seaward. To the west, there was a transition to erosion and loss of area in the beach and dune in Profiles SH11 and SH12. The entire bayside of Sandy Hook from 2012 to 2017 was comparatively stable. There was some erosion on the bayside profiles, less than on the more exposed oceanside.

Table 14. Net change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Sandy Hook Unit, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012- Spring 2017	SH1	-35.37 \pm 0.03	-39.36 \pm 0.03	0.54 \pm 0.06	-48.45 \pm 6.22	-9.38 \pm 2.38	-39.07 \pm 3.95
	SH2	-52.28 \pm 0.03	-23.58 \pm 0.03	-0.51 \pm 0.06	-55.79 \pm 10.43	-12.38 \pm 2.71	-43.41 \pm 7.72
	SH3	-28.74 \pm 0.03	-6.05 \pm 0.03	-0.33 \pm 0.06	-6.39 \pm 12.49	-14.11 \pm 4.84	7.72 \pm 7.69
	SH4	-2.23 \pm 0.03	-15.57 \pm 0.03	0.08 \pm 0.06	-38.52 \pm 8.56	-63.49 \pm 4.62	24.97 \pm 3.96
	SH5	-29.64 \pm 0.03	-35.72 \pm 0.03	-0.36 \pm 0.06	-74.33 \pm 5.52	-17.77 \pm 2.94	-56.56 \pm 2.59
	SH6	-55.42 \pm 0.03	-43.63 \pm 0.03	0.22 \pm 0.06	-194.94 \pm 8.69	-47.96 \pm 4.54	-146.97 \pm 4.18
	SH7	30.82 \pm 0.03	0.01 \pm 0.03	0.03 \pm 0.06	43.48 \pm 26.68	-2.12 \pm 7.01	45.60 \pm 19.67
	SH8	70.20 \pm 0.03	-1.94 \pm 0.03	0.31 \pm 0.06	152.35 \pm 22.82	13.41 \pm 7.07	138.94 \pm 15.85
	SH9.1*	-36.56 \pm 0.75	-1.47 \pm 0.75	-0.24 \pm 0.20	-124.31 \pm 55.10	-46.41 \pm 41.96	-77.90 \pm 13.15
	SH9.2*	46.17 \pm 0.75	12.22 \pm 0.75	0.61 \pm 0.20	167.07 \pm 143.58	-6.75 \pm 26.06	173.82 \pm 117.52
	SH10	122.92 \pm 0.03	3.32 \pm 0.03	0.75 \pm 0.06	129.20 \pm 20.70	44.87 \pm 10.25	84.33 \pm 10.56
	SH11	-46.63 \pm 0.03	-62.78 \pm 0.03	-1.11 \pm 0.06	-135.55 \pm 8.63	-58.41 \pm 7.66	-77.15 \pm 1.03
	SH12	-8.54 \pm 0.03	-4.29 \pm 0.03	-0.17 \pm 0.06	-25.37 \pm 8.26	-12.70 \pm 4.70	-12.67 \pm 3.56
	SH13	2.03 \pm 0.03	0.54 \pm 0.03	0.46 \pm 0.06	5.05 \pm 4.87	4.14 \pm 0.56	0.90 \pm 4.34
	SH14	-4.57 \pm 0.03	-0.10 \pm 0.03	-0.20 \pm 0.06	-5.42 \pm 2.72	-0.07 \pm 0.39	-5.34 \pm 2.33
	SH15	-2.17 \pm 0.03	0.34 \pm 0.03	-0.07 \pm 0.06	8.95 \pm 3.45	0.83 \pm 0.68	8.13 \pm 2.80
	SH16	-3.17 \pm 0.03	-3.22 \pm 0.03	-0.10 \pm 0.06	-15.59 \pm 1.85	-9.26 \pm 1.35	-6.32 \pm 0.51

* No Spring 2012 or 2013 surveys conducted, initial profile is LiDAR 2010.

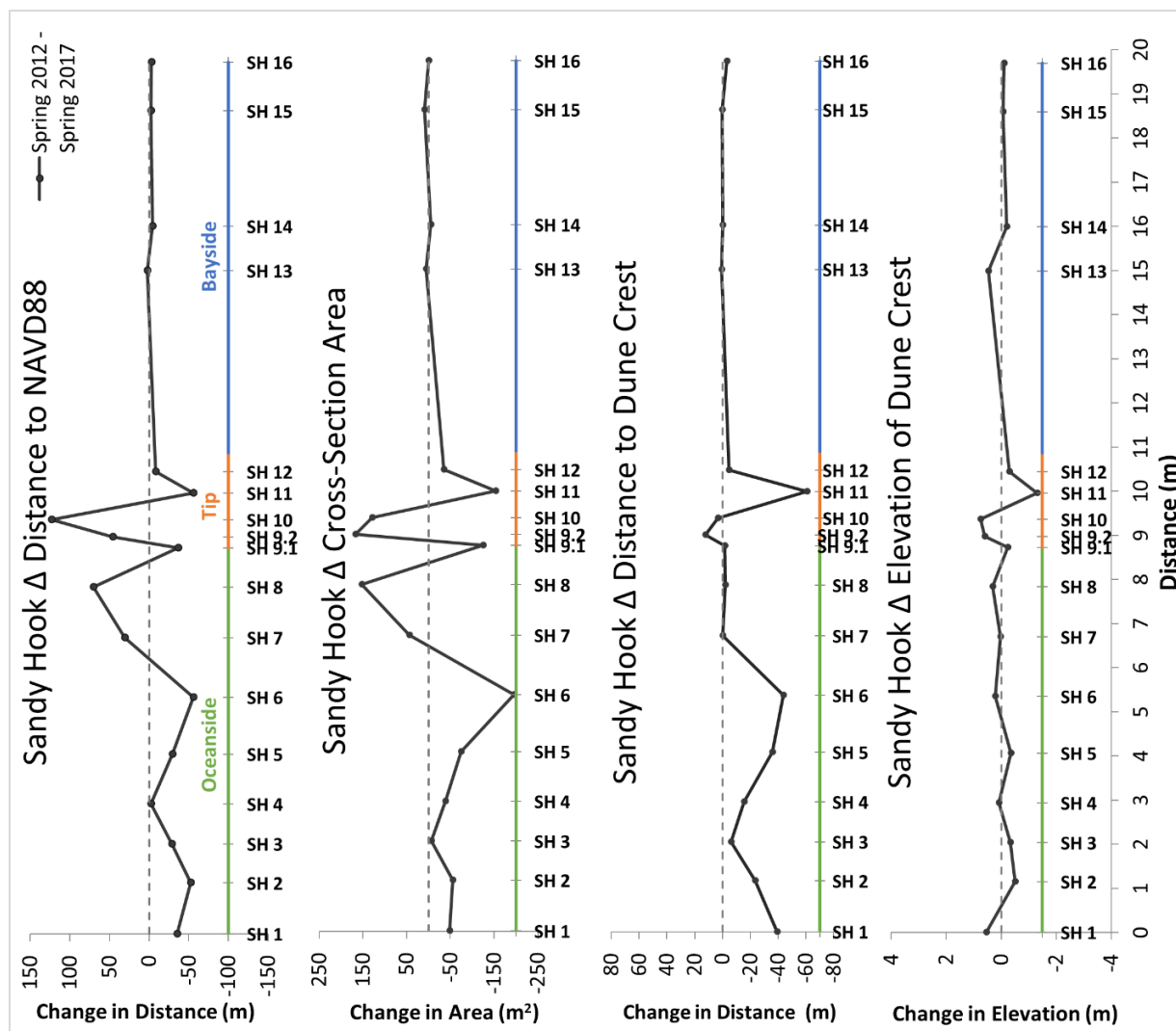


Figure 46. Alongshore dimensions of selected topographical variables within the Sandy Hook Unit, Gateway National Recreation Area, from Spring 2012 to Spring 2017, incorporating dune/beach profile sites along the oceanside, northern tip, and bayside.

Jamaica Bay Unit

Breezy Point

Breezy Point is a part of the Rockaway barrier island that extends to New York Harbor. The dominant sediment transport direction is to the southeast along the oceanside and to the north east on the bayside. Prior to Hurricane Sandy, there was a relatively continuous foredune feature along NPS beaches and gaps in the dune feature on community beaches. Areas of this foredune were eliminated in Fort Tilden and near Breezy Point Tip during Hurricane Sandy. There are a number of hard structures such as wooden and stone groins along both the oceanside and the bayside and a jetty at the western margin of the site. A detailed report of the geomorphology of Breezy Point is available (Psuty et al. 2015a; Psuty et al. 2017b). The surveyed area is downdrift of the Rockaways, a site of a large beach nourishment project in 2014 (Table 2). Some of this sediment was also placed directly in Jacob Riis Park, the placement of this sediment affected the profiles in the area and downdrift. Eleven monuments have been established along the ocean and bay shoreline at Breezy Point (Figure 47). The location, description, and coordinates of the Breezy Point monuments are detailed in a booklet prepared for this purpose (Psuty et al. 2010c).

The Spring 2012 survey was not collected; thus, the Spring 2011 survey was used as the initial profile.

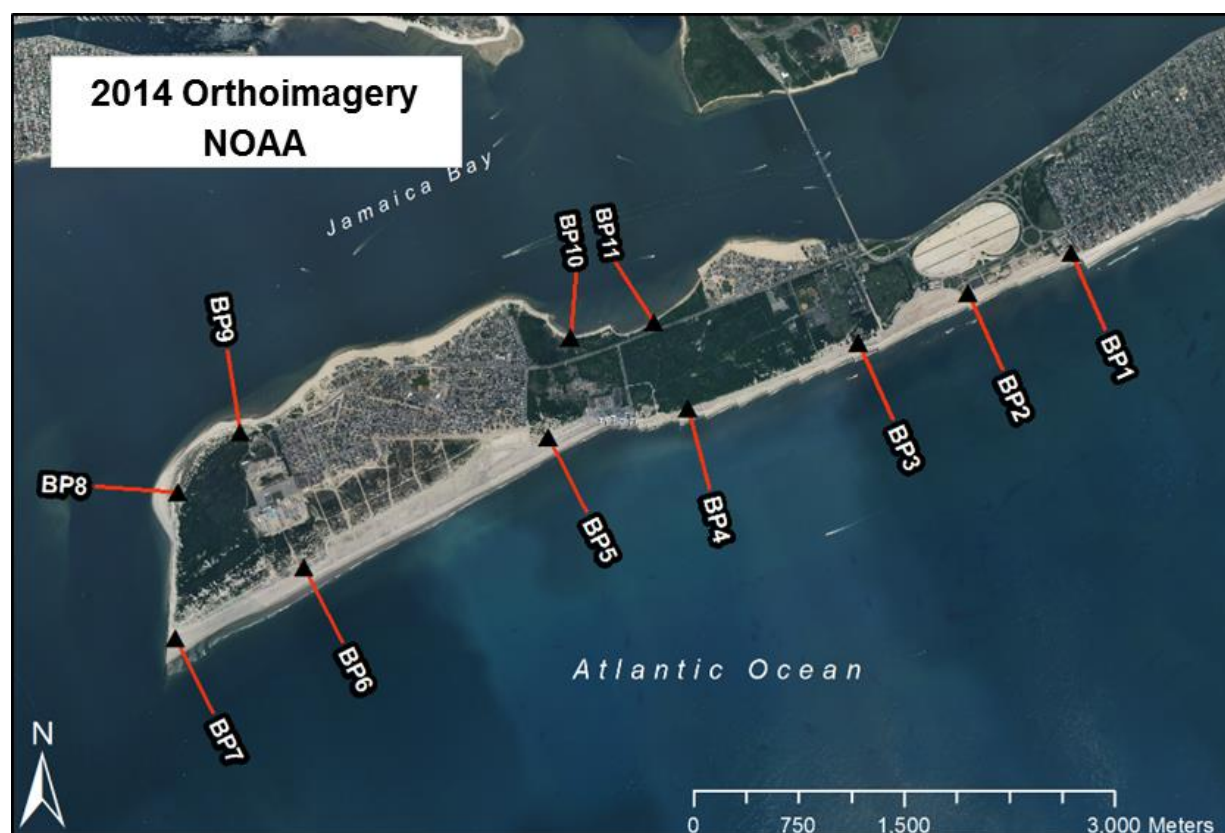


Figure 47. Site of coastal topography profiles along Breezy Point within the Jamaica Bay Unit of Gateway National Recreation Area.

Annual Topography Change

From Spring 2011 to Spring 2013, the foredune feature was eliminated, and the dune feature lost cross-section area in all of the oceanside profiles, where present (Figure 48 – Figure 51; Table 15). The 2013 foredune crest location was displaced -3 m to -52 m inland of the pre-storm 2011 location. There was also erosion in the beach feature along the oceanside, except for BP7 due to area gain because of overwash. Post-storm recovery along the oceanside has generally taken the form of annual gain in the beach feature, with the intersection with NAVD88 moving seaward. Part of this gain in the beach feature may be attributed to the large nourishment episode in 2014. The foredune crest position has remained relatively stable in the inland post-storm position, though the dune has gained in elevation and cross-section area.

Profiles BP8 and BP9 along Breezy Point Bayside gained area from Spring 2011 to Spring 2013, the opposite trend of the erosion along the oceanside (Figure 52; Table 15). Post-storm, these two profiles have continued to gain area in the beach and dune features. The remaining two bayside profiles, BP 10 and BP 11, were eroded during Hurricane Sandy, and the erosion has continued in the dune feature to the Spring 2017 survey (Figure 53; Table 15). Sediment was trapped by two stone groins on either side of the cove where BP10 and BP11 are located, perhaps contributing to the continued erosion of these profiles.

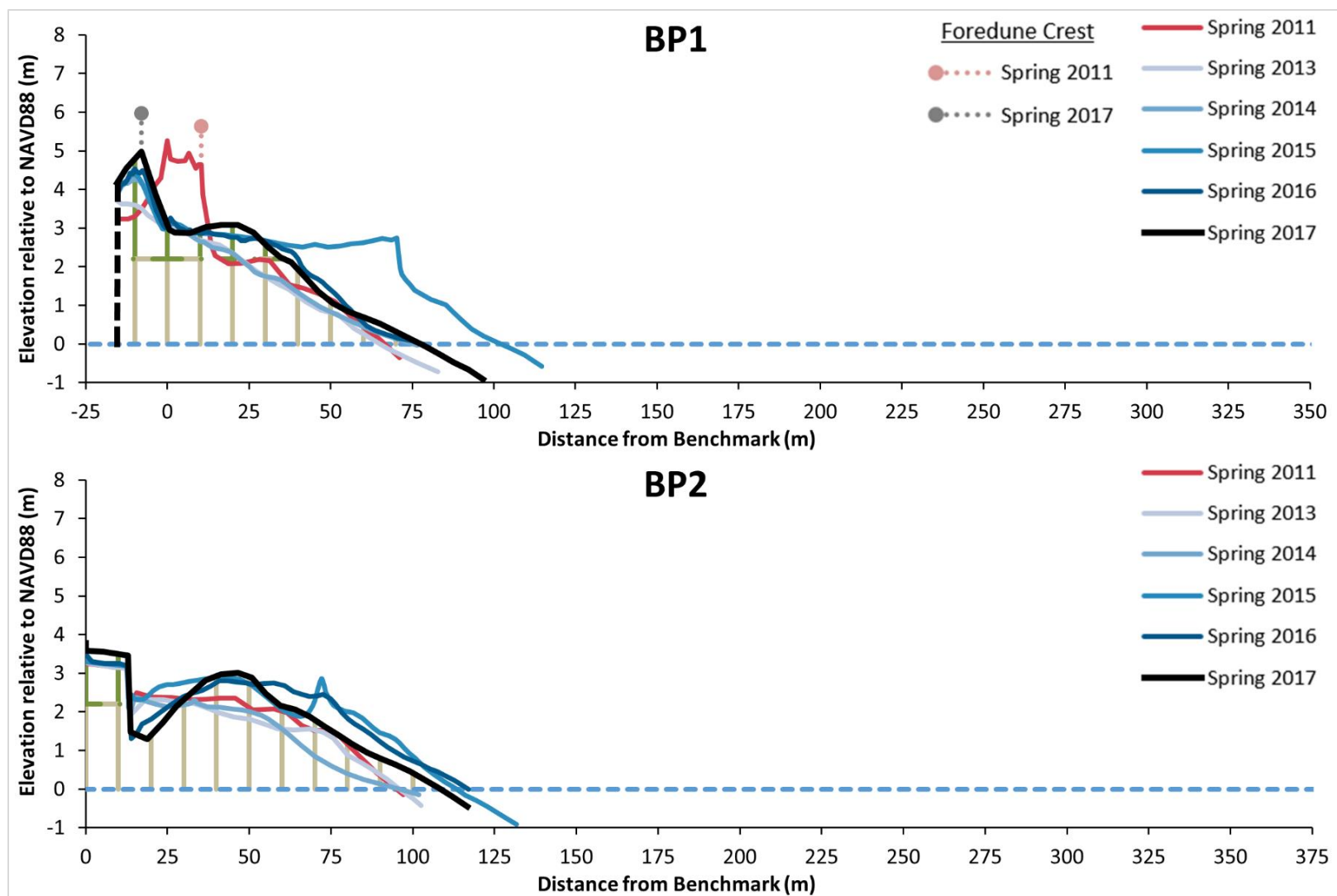


Figure 48. Coastal topography of Profiles BP1 and BP2 along the oceanside of Breezy Point within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

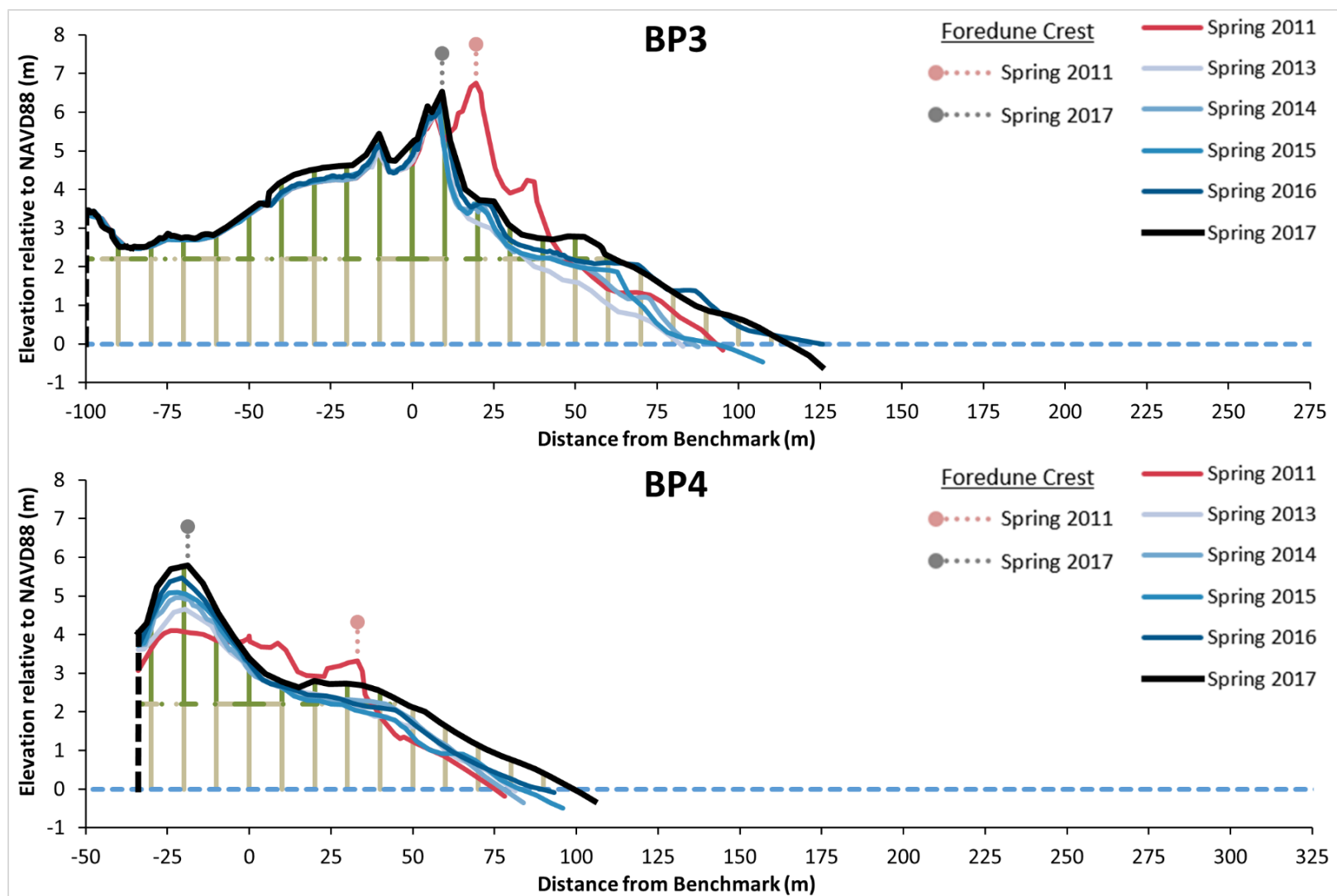


Figure 49. Coastal topography of Profiles BP3 and BP4 along the oceanside of Breezy Point within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

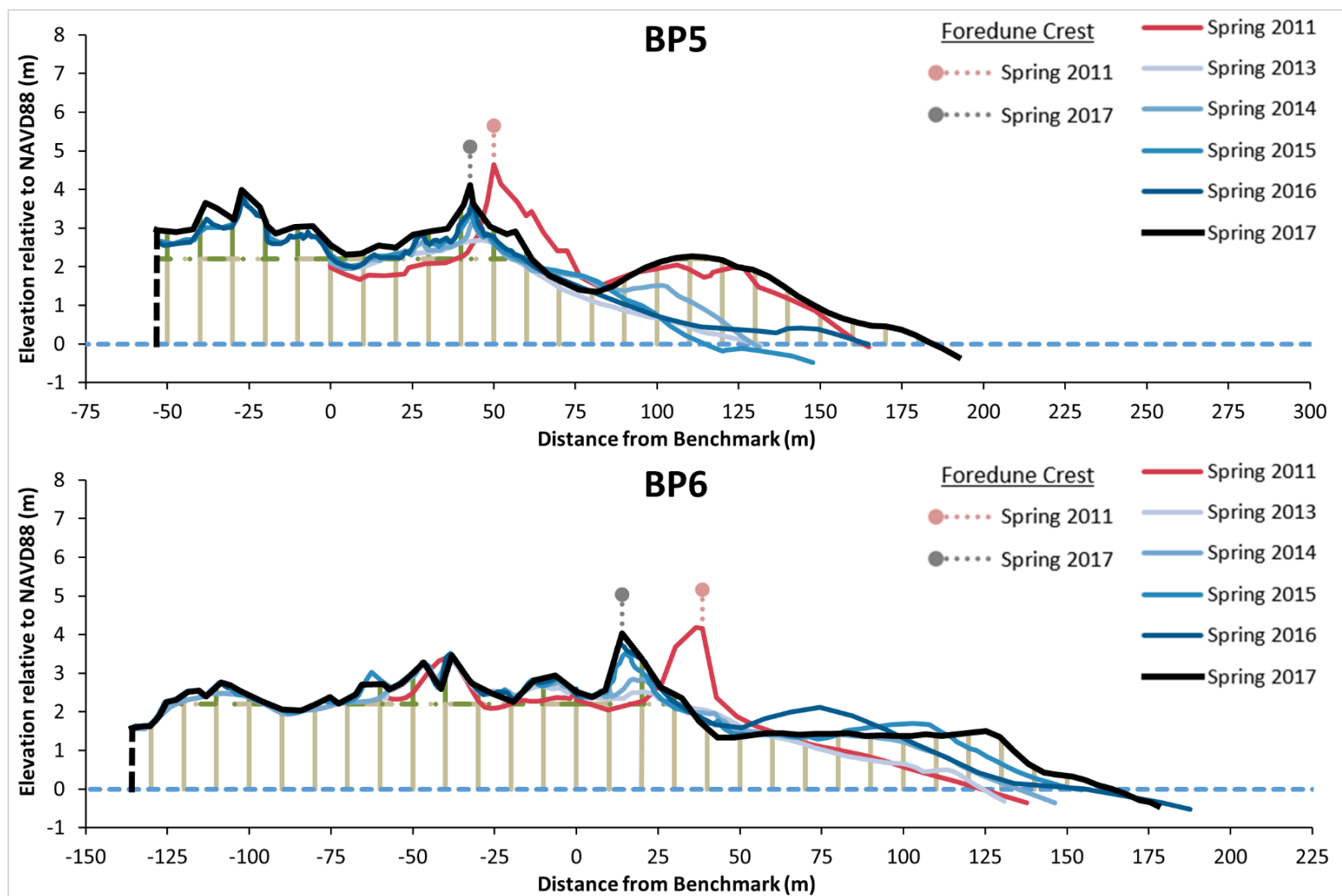


Figure 50. Coastal topography of Profiles BP5 and BP6 along the oceanside of Breezy Point within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

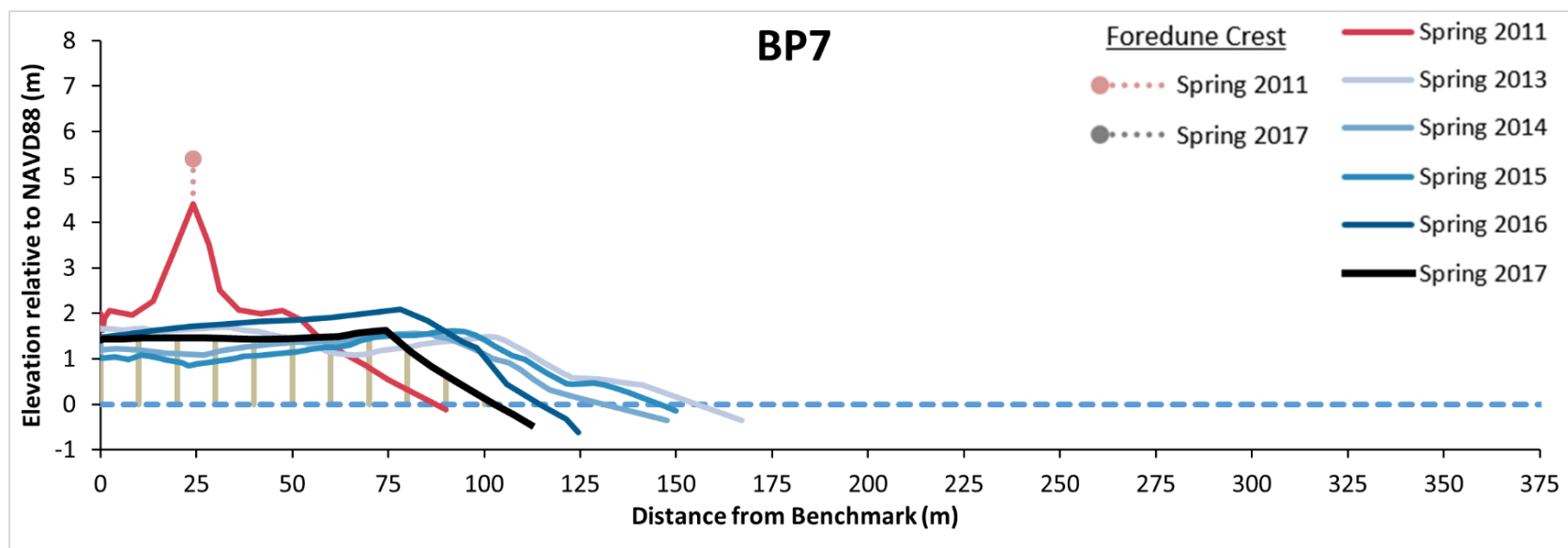


Figure 51. Coastal topography of Profiles BP7 along the oceanside of Breezy Point within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

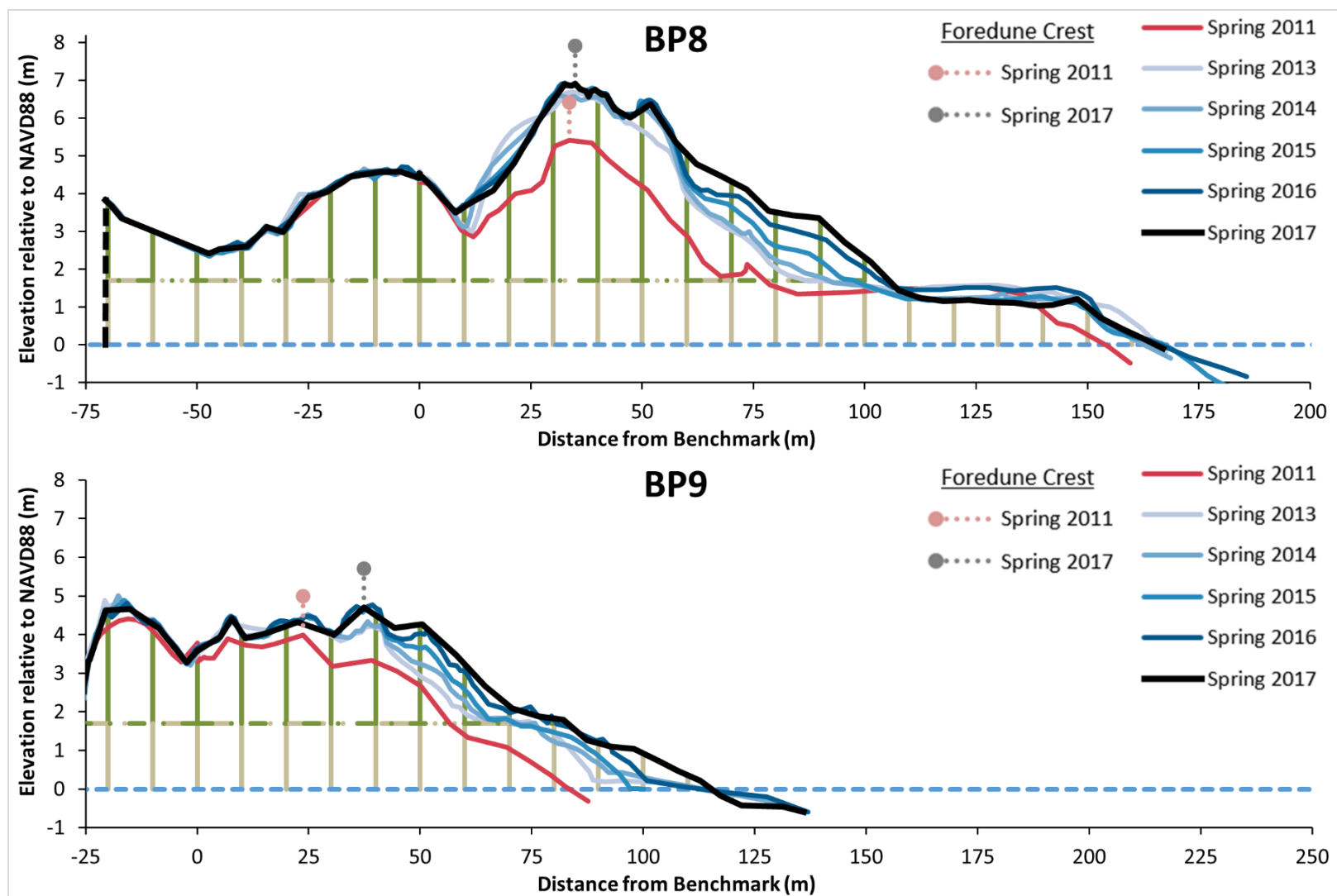


Figure 52. Coastal topography of Profiles BP8 and BP9 along the bayside of Breezy Point within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

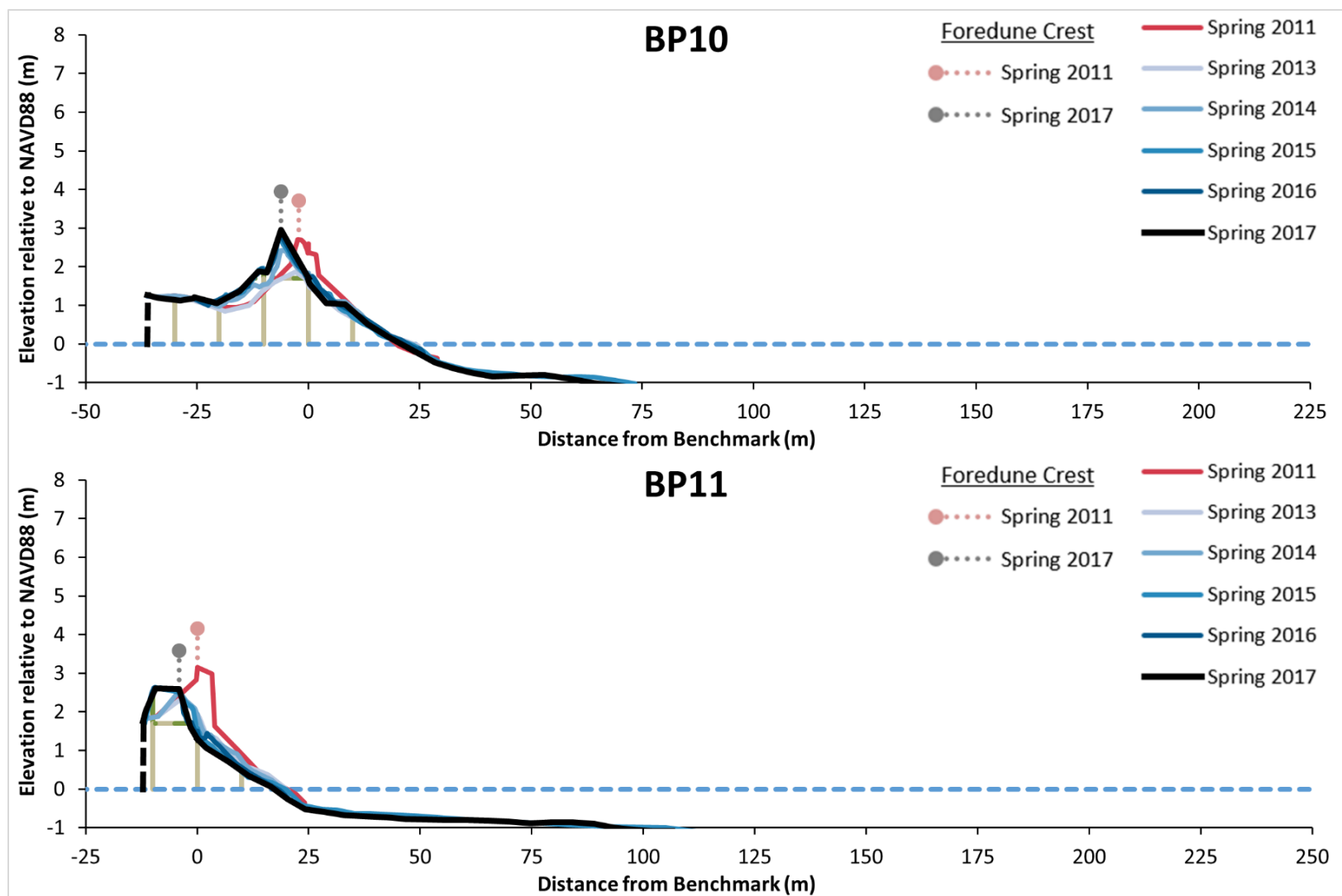


Figure 53. Coastal topography of Profiles BP10 and BP11 along the bayside of Breezy Point within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

Table 15. Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Breezy Point, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2011- Spring 2013	BP1	-1.31 \pm 0.03	-25.84 \pm 0.03	-0.93 \pm 0.06	-35.35 \pm 4.60	-24.72 \pm 1.97	-10.62 \pm 2.64
	BP2	0.94 \pm 0.03	—	—	-16.29 \pm 5.40	-0.14 \pm 0.75	-16.15 \pm 4.64
	BP3	-10.98 \pm 0.03	-12.09 \pm 0.03	-0.79 \pm 0.06	-90.78 \pm 10.62	-63.55 \pm 7.98	-27.23 \pm 2.64
	BP4	5.55 \pm 0.03	-52.76 \pm 0.03	1.35 \pm 0.06	-12.56 \pm 6.33	-22.18 \pm 3.89	9.62 \pm 2.46
	BP5	-32.74 \pm 0.03	-3.30 \pm 0.03	-1.95 \pm 0.06	-118.25 \pm 11.34	-23.03 \pm 6.69	-95.22 \pm 4.65
	BP6	0.31 \pm 0.03	-15.80 \pm 0.03	-1.68 \pm 0.06	-11.81 \pm 14.72	-8.90 \pm 7.45	-2.90 \pm 7.26
	BP7	68.11 \pm 0.03	—	—	22.28 \pm 7.13	-19.68 \pm 0.77	41.95 \pm 6.79
	BP8	11.86 \pm 0.03	0.10 \pm 0.03	1.27 \pm 0.06	119.61 \pm 13.05	92.93 \pm 8.65	26.68 \pm 4.40
	BP9	29.15 \pm 0.03	15.26 \pm 0.03	0.22 \pm 0.06	64.27 \pm 7.04	38.13 \pm 5.20	26.13 \pm 1.84
	BP10	3.71 \pm 0.03	-0.72 \pm 0.03	-0.84 \pm 0.06	-9.32 \pm 3.27	-4.73 \pm 0.45	-4.59 \pm 2.86
	BP11	-0.15 \pm 0.03	-4.06 \pm 0.03	-0.85 \pm 0.06	-9.85 \pm 1.82	-7.08 \pm 0.83	-2.77 \pm 1.00
Spring 2013- Spring 2014	BP1	10.20 \pm 0.03	6.08 \pm 0.03	0.54 \pm 0.06	10.98 \pm 4.85	6.19 \pm 2.13	4.79 \pm 2.73
	BP2	0.08 \pm 0.03	—	—	-10.83 \pm 5.43	0.82 \pm 0.75	-11.65 \pm 4.68
	BP3	3.67 \pm 0.03	-1.16 \pm 0.03	-0.07 \pm 0.06	25.07 \pm 10.41	4.93 \pm 8.03	20.14 \pm 2.41
	BP4	-2.97 \pm 0.03	0.25 \pm 0.03	0.24 \pm 0.06	10.15 \pm 6.40	6.16 \pm 4.01	3.98 \pm 2.42
	BP5	-0.55 \pm 0.03	-3.68 \pm 0.03	0.44 \pm 0.06	35.67 \pm 10.36	2.56 \pm 6.06	33.11 \pm 4.30
	BP6	10.88 \pm 0.03	-2.82 \pm 0.03	0.37 \pm 0.06	32.38 \pm 15.04	6.55 \pm 7.32	25.83 \pm 7.72
	BP7	-24.22 \pm 0.03	—	—	-36.01 \pm 8.14	—	-36.01 \pm 8.14
	BP8	-3.18 \pm 0.03	2.52 \pm 0.03	-0.21 \pm 0.06	-141.97 \pm 11.48	572.02 \pm 28.02	-714.00 \pm 21.04
	BP9	1.28 \pm 0.03	-0.81 \pm 0.03	0.12 \pm 0.06	7.98 \pm 7.85	3.98 \pm 5.58	4.00 \pm 2.28
	BP10	-1.72 \pm 0.03	-2.87 \pm 0.03	0.56 \pm 0.06	8.50 \pm 3.33	2.68 \pm 0.40	5.81 \pm 2.95
	BP11	-1.09 \pm 0.03	0.01 \pm 0.03	0.23 \pm 0.06	0.55 \pm 1.78	0.88 \pm 0.73	-0.32 \pm 1.05
Spring 2014- Spring 2015	BP1	26.69 \pm 0.03	-1.03 \pm 0.03	0.26 \pm 0.06	108.29 \pm 5.94	25.98 \pm 3.77	82.30 \pm 2.46
	BP2	17.27 \pm 0.03	—	—	82.75 \pm 5.94	0.09 \pm 0.53	82.66 \pm 5.61
	BP3	7.13 \pm 0.03	1.11 \pm 0.03	0.28 \pm 0.06	2.91 \pm 10.72	3.00 \pm 8.24	-0.09 \pm 2.50
	BP4	5.27 \pm 0.03	-2.52 \pm 0.03	0.18 \pm 0.06	-2.42 \pm 6.46	4.04 \pm 3.86	-6.46 \pm 2.71
	BP5	-15.08 \pm 0.03	-0.37 \pm 0.03	0.37 \pm 0.06	-17.40 \pm 9.93	5.08 \pm 5.84	-22.48 \pm 4.09
	BP6	18.01 \pm 0.03	-5.17 \pm 0.03	0.66 \pm 0.06	40.25 \pm 15.86	13.71 \pm 7.55	26.54 \pm 8.31

Table 15 (continued). Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Breezy Point, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2014- Spring 2015 (cont.)	BP7	14.51 \pm 0.03	–	–	3.12 \pm 7.85	–	3.12 \pm 7.85
	BP8	4.39 \pm 0.03	-0.45 \pm 0.03	0.31 \pm 0.06	151.31 \pm 11.52	-545.63 \pm 28.12	696.95 \pm 20.98
	BP9	-14.01 \pm 0.03	1.08 \pm 0.03	0.41 \pm 0.06	10.94 \pm 7.50	11.27 \pm 5.47	-0.33 \pm 2.06
	BP10	1.03 \pm 0.03	-0.84 \pm 0.03	0.33 \pm 0.06	1.92 \pm 3.31	2.15 \pm 0.60	-0.23 \pm 2.72
	BP11	0.94 \pm 0.03	-0.07 \pm 0.03	-0.02 \pm 0.06	-1.04 \pm 1.78	2.58 \pm 0.69	-3.62 \pm 1.09
Spring 2015- Spring 2016	BP1	-24.10 \pm 0.03	0.39 \pm 0.03	0.03 \pm 0.06	-75.00 \pm 6.00	-11.77 \pm 4.11	-63.23 \pm 1.96
	BP2	3.76 \pm 0.03	–	–	-9.78 \pm 6.51	0.22 \pm 0.53	-10.00 \pm 6.14
	BP3	32.53 \pm 0.03	2.31 \pm 0.03	0.00 \pm 0.06	56.17 \pm 11.87	12.56 \pm 8.23	43.61 \pm 3.68
	BP4	5.95 \pm 0.03	1.33 \pm 0.03	0.38 \pm 0.06	17.97 \pm 6.78	8.98 \pm 3.58	8.99 \pm 3.21
	BP5	49.80 \pm 0.03	0.70 \pm 0.03	0.21 \pm 0.06	13.63 \pm 10.99	1.43 \pm 5.75	12.20 \pm 5.34
	BP6	2.28 \pm 0.03	-0.36 \pm 0.03	0.19 \pm 0.06	7.61 \pm 16.42	7.25 \pm 7.95	0.36 \pm 8.48
	BP7	-31.39 \pm 0.03	–	–	31.97 \pm 7.41	–	31.97 \pm 7.41
	BP8	-0.86 \pm 0.03	-2.06 \pm 0.03	0.09 \pm 0.06	35.68 \pm 13.42	20.35 \pm 9.69	15.33 \pm 3.73
	BP9	12.83 \pm 0.03	0.00 \pm 0.03	0.02 \pm 0.06	22.04 \pm 7.47	12.04 \pm 5.75	10.00 \pm 1.72
	BP10	-0.39 \pm 0.03	0.05 \pm 0.03	0.06 \pm 0.06	2.06 \pm 3.32	0.26 \pm 0.69	1.80 \pm 2.63
	BP11	-1.77 \pm 0.03	-0.29 \pm 0.03	0.07 \pm 0.06	0.33 \pm 1.75	-0.73 \pm 0.62	1.06 \pm 1.14
Spring 2016- Spring 2017	BP1	-0.42 \pm 0.03	2.09 \pm 0.03	0.44 \pm 0.06	4.80 \pm 5.27	6.34 \pm 3.02	-1.54 \pm 2.25
	BP2	-8.52 \pm 0.03	–	–	-24.67 \pm 6.38	3.73 \pm 0.76	-28.40 \pm 5.62
	BP3	-10.25 \pm 0.03	-0.65 \pm 0.03	0.34 \pm 0.06	30.97 \pm 12.47	32.62 \pm 8.79	-1.65 \pm 3.75
	BP4	10.39 \pm 0.03	1.72 \pm 0.03	0.33 \pm 0.06	47.18 \pm 7.25	22.22 \pm 4.22	24.95 \pm 3.04
	BP5	20.16 \pm 0.03	-0.67 \pm 0.03	0.40 \pm 0.06	132.82 \pm 12.89	33.94 \pm 6.56	98.87 \pm 6.37
	BP6	8.26 \pm 0.03	-0.38 \pm 0.03	0.33 \pm 0.06	11.00 \pm 16.72	1.56 \pm 8.11	9.44 \pm 8.61
	BP7	-11.63 \pm 0.03	–	–	-51.18 \pm 6.15	–	-51.18 \pm 6.15
	BP8	-0.85 \pm 0.03	1.24 \pm 0.03	0.04 \pm 0.06	-0.41 \pm 13.37	13.04 \pm 9.91	-13.45 \pm 3.47
	BP9	2.64 \pm 0.03	-1.92 \pm 0.03	-0.07 \pm 0.06	11.80 \pm 7.90	3.45 \pm 6.07	8.35 \pm 1.82
	BP10	-1.57 \pm 0.03	0.38 \pm 0.03	0.14 \pm 0.06	-0.69 \pm 3.27	1.01 \pm 0.70	-1.70 \pm 2.56
	BP11	-0.85 \pm 0.03	0.31 \pm 0.03	0.00 \pm 0.06	-2.59 \pm 1.68	0.17 \pm 0.59	-2.76 \pm 1.09

6-year Topography Change

From Spring 2011 to Spring 2017, profiles along Breezy Point Oceanside gained in cross-section area, 83% of this gain occurred in the beach area (Table 16, Figure 54). This gain in the beach along the oceanside was likely due to a combination of post-storm recovery and the large 2014 nourishment project updrift and within Jacob Riis Park. The dune feature was displaced inland due to Hurricane Sandy, an inland displacement ranging from -7 m to -51 m from the initial survey to the 2017 survey. The western two profiles along Breezy Point Bayside (BP8 and BP9) also gained in cross-section area during the survey period. However, the majority of this gain was in the dune feature, accounting for 79% of total area gain. The two eastern bayside profiles were not as accretional, with BP10 gaining +3 m² of area and BP11 eroding -13m² of area.

Table 16. Net change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Breezy Point, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2011-Spring 2017	BP1	11.05 \pm 0.03	-18.32 \pm 0.03	0.34 \pm 0.06	13.72 \pm 4.95	2.02 \pm 2.41	11.69 \pm 2.61
	BP2	13.52 \pm 0.03	—	—	21.17 \pm 5.77	4.72 \pm 0.76	16.45 \pm 5.01
	BP3	22.09 \pm 0.03	-10.47 \pm 0.03	-0.23 \pm 0.06	24.33 \pm 11.57	-10.43 \pm 8.75	34.77 \pm 2.82
	BP4	24.19 \pm 0.03	-51.98 \pm 0.03	2.47 \pm 0.06	60.31 \pm 6.89	19.23 \pm 4.35	41.08 \pm 2.54
	BP5	21.59 \pm 0.03	-7.32 \pm 0.03	-0.53 \pm 0.06	46.46 \pm 12.86	19.98 \pm 7.22	26.48 \pm 5.65
	BP6	39.75 \pm 0.03	-24.52 \pm 0.03	-0.13 \pm 0.06	79.43 \pm 15.87	20.17 \pm 7.84	59.26 \pm 8.04
	BP7	15.38 \pm 0.03	—	—	-29.81 \pm 5.40	-19.68 \pm 0.77	-10.13 \pm 4.93
	BP8	11.36 \pm 0.03	1.34 \pm 0.03	1.49 \pm 0.06	164.22 \pm 13.03	152.71 \pm 9.20	11.51 \pm 3.89
	BP9	31.89 \pm 0.03	13.62 \pm 0.03	0.71 \pm 0.06	117.04 \pm 7.13	68.87 \pm 5.45	48.16 \pm 1.68
	BP10	1.04 \pm 0.03	-4.00 \pm 0.03	0.24 \pm 0.06	2.46 \pm 3.19	1.37 \pm 0.65	1.10 \pm 2.55
	BP11	-2.93 \pm 0.03	-4.10 \pm 0.03	-0.56 \pm 0.06	-12.59 \pm 1.74	-4.18 \pm 0.76	-8.42 \pm 1.00

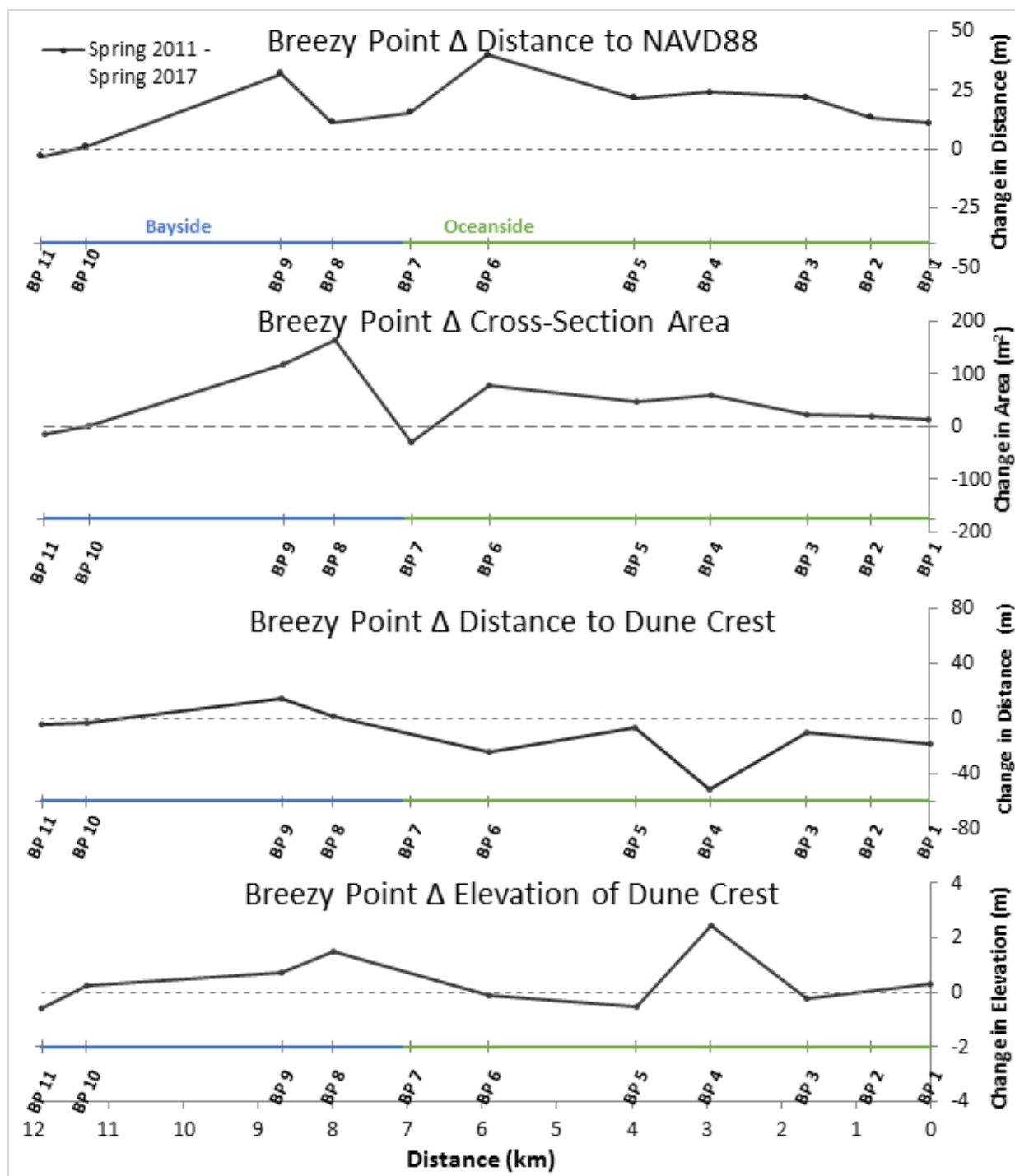


Figure 54. Alongshore dimensions of selected topographical variables at Breezy Point within the Jamaica Bay Unit, Gateway National Recreation Area, from Spring 2011 – Spring 2017, incorporating dune/beach profile sites along the bayside and the oceanside.

Plumb Beach

Plumb Beach has an ocean-facing shoreline near the Belt Parkway in Brooklyn. The dominant sediment transport direction is to the west in the Western Portion of the site and to the east in the

Eastern Portion of the site. In 2012, a major beach nourishment project placed 127,000 yds³ (97,000 m³) at Plumb Beach (Table 2). In 2013, construction continued, a stone breakwater and two stone groins were built to contain the 2012 fill. A detailed report of the geomorphology of Plumb Beach is available (Psuty et al. 2015a; Psuty et al. 2017b). Five monuments have been established along the ocean-facing shoreline of Plumb Beach (Figure 55). The location, description, and coordinates of the Plumb Beach monuments are detailed in a booklet prepared for this purpose (Psuty et al. 2010f). Profiles PB1 – PB3 are within the anthropogenic portion of the shoreline and Profiles PB4 – PB5 are on the less anthropogenically influenced eastern end, though the restriction of sediment caused by the stone groin did affect PB4.

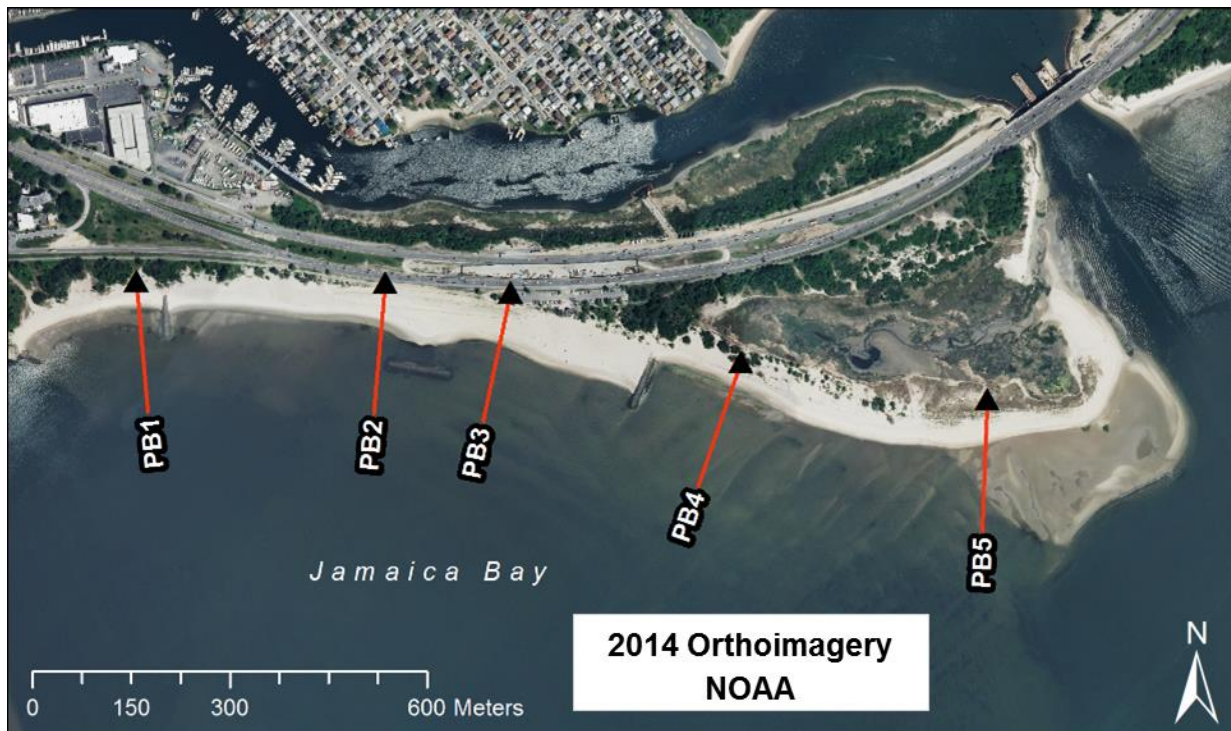


Figure 55. Site of coastal topography profiles at Plumb Beach site within the Jamaica Bay Unit, Gateway National Recreation Area.

Annual Topography Change

Profile PB1 was located just west of the sediment placement and construction and was relatively stable throughout the survey period (Figure 56). There was annually little change in the beach feature, and some consistent growth in the dune feature. The two profiles within the construction area changed drastically due to the 2012 and 2013 fill and construction (Figure 56 and Figure 57). From Spring 2012 to Spring 2013, there was a gain of approximately $+120 \text{ m}^2$ of cross-section area on each profile. Post-construction however, erosion in the beach and dune feature has persisted on both PB2 and PB3, with an average loss of -5 m^2 per year from Spring 2013 to Spring 2017 (Table 17). The elevation and position of the constructed foredune crest was relatively stable, however erosion scarped the base of the foredune.

Profiles PB4 and PB5 were outside of the constructed structures. In both profiles, the foredune was eroded during Hurricane Sandy and caused an inland displacement of the foredune crest of -1 m to -7 m (Figure 57 and Figure 58). PB4 also lost cross-section area in the beach, whereas PB5 gained area in the beach feature. Due to the easterly direction of sediment transport in this area, the erosion on PB4 was caused by the updrift groin restricting sediment transport. Also, the erosion on PB4 may have fed the accretion on the beach in PB5. Post-storm, the beach feature at PB4 has continued to erode, feeding the continued accretion in the beach of PB5.

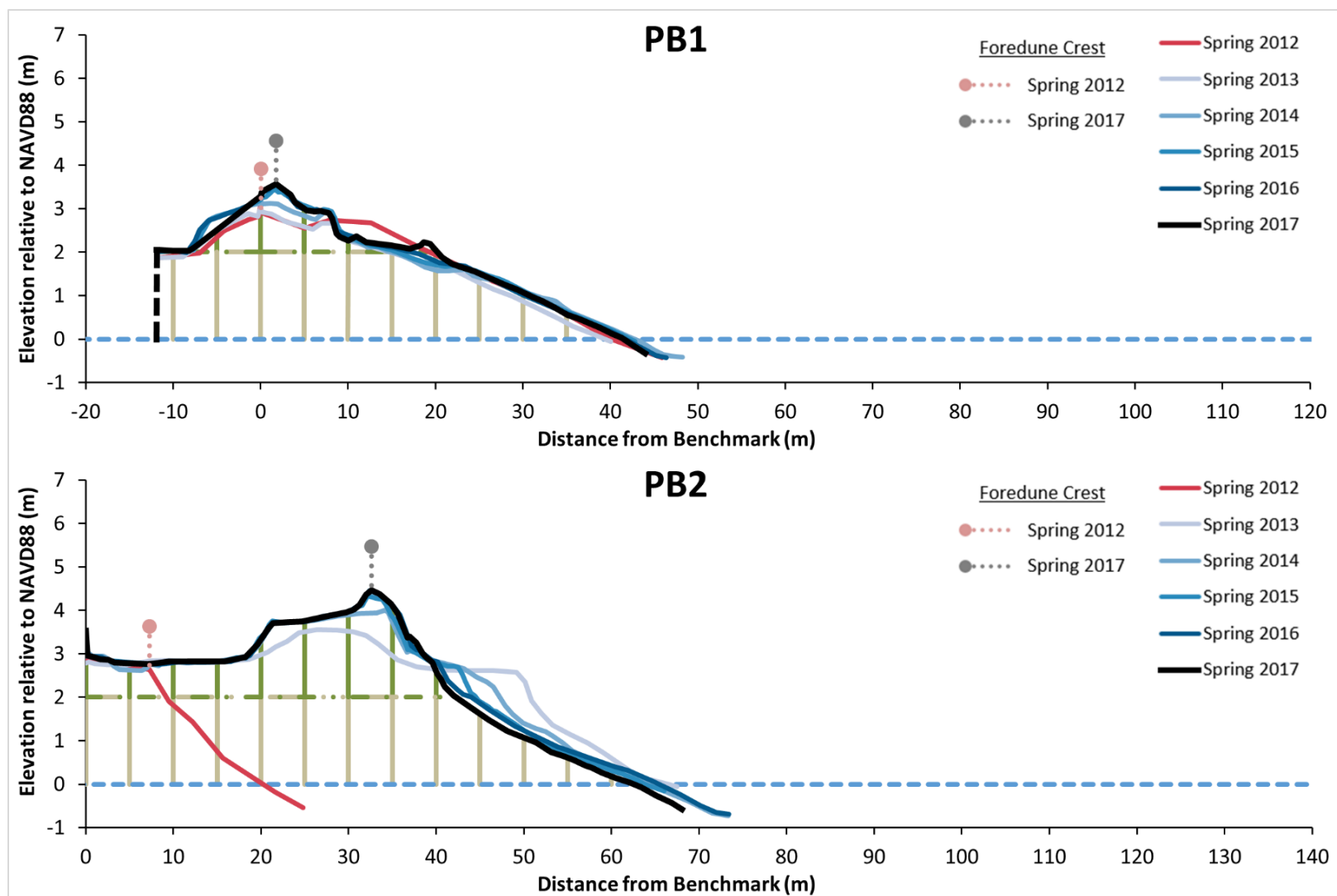


Figure 56. Coastal topography of Profiles PB1 and PB2 at Plumb Beach within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

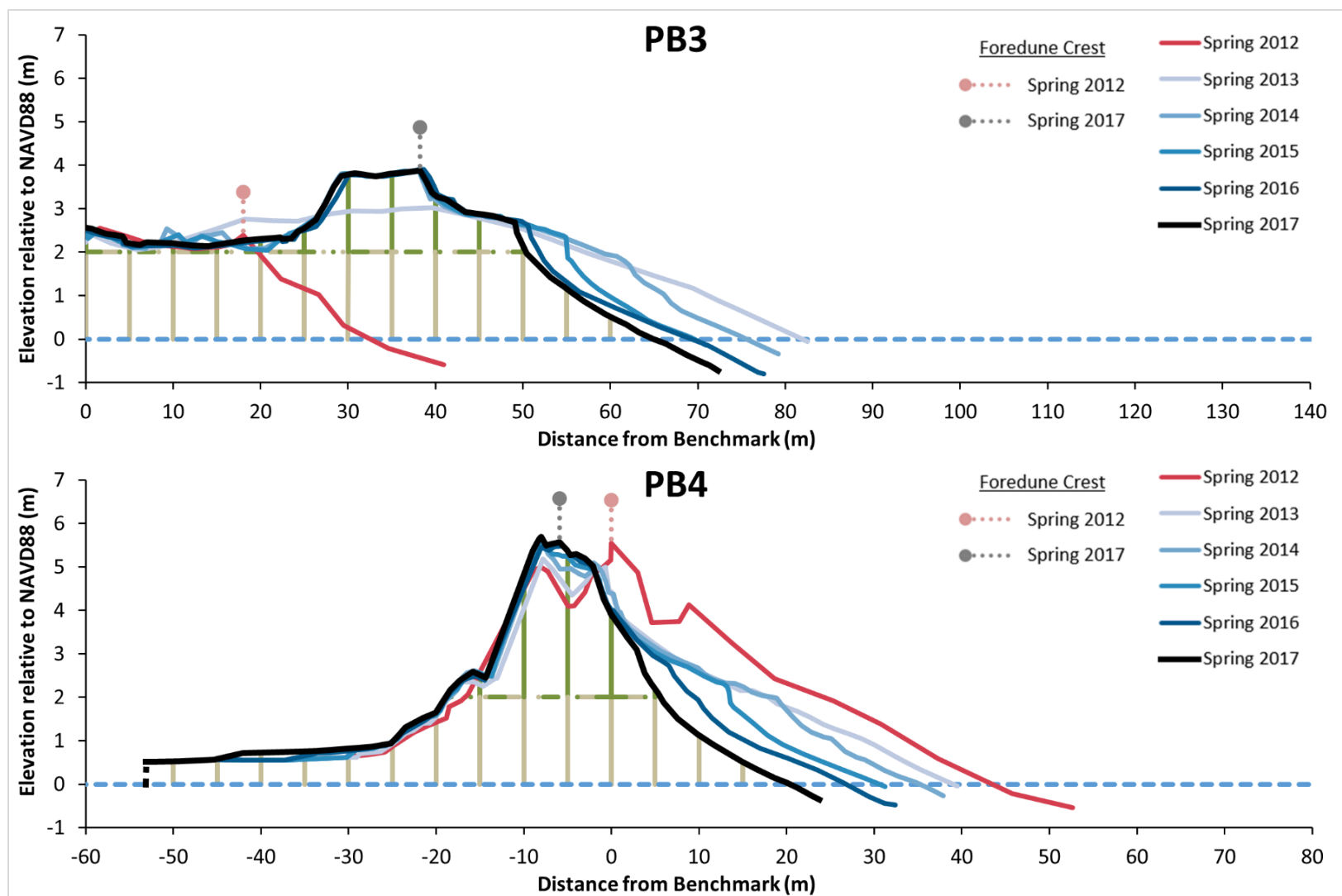


Figure 57. Coastal topography of Profiles PB3 and PB4 at Plumb Beach within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

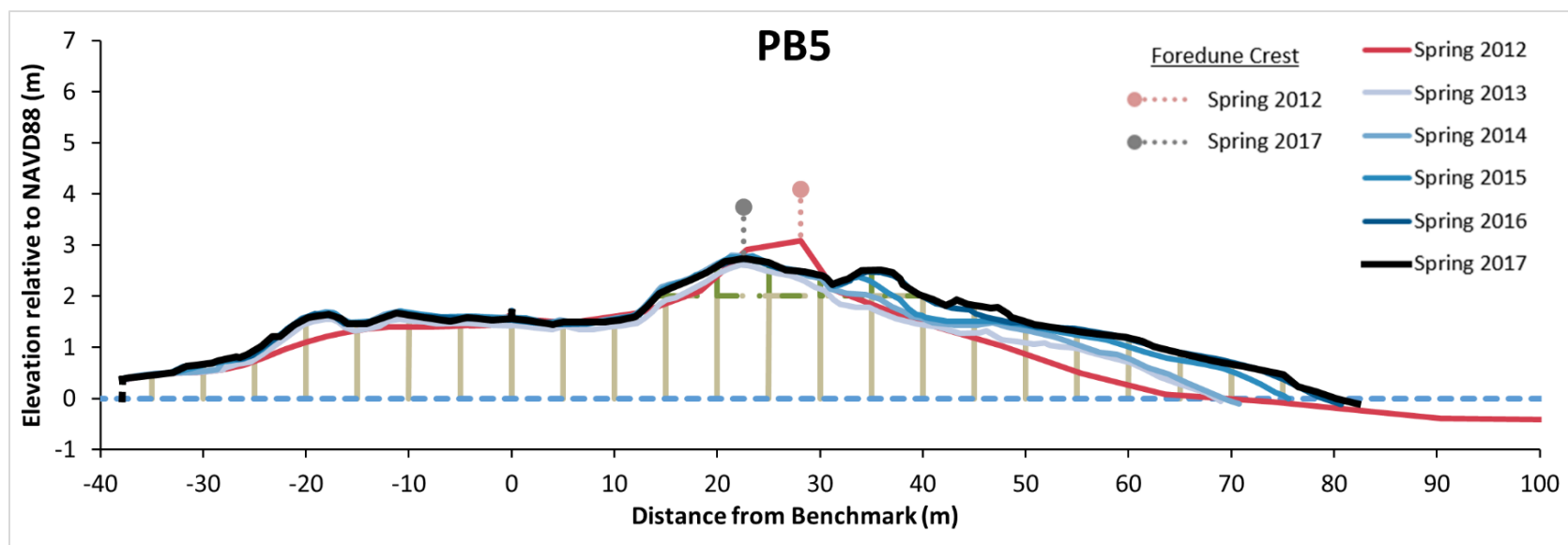


Figure 58. Coastal topography of Profile PB5 at Plumb Beach within the Jamaica Bay Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line if present, color coded respectively.

Table 17. Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Plumb Beach, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012-Spring 2013	PB1	-0.74 \pm 0.03	0.11 \pm 0.03	0.01 \pm 0.06	-7.01 \pm 2.92	-2.89 \pm 1.39	-4.12 \pm 1.53
	PB2	46.26 \pm 0.03	19.15 \pm 0.03	0.92 \pm 0.06	126.10 \pm 2.78	40.61 \pm 2.06	85.49 \pm 0.77
	PB3	49.41 \pm 0.03	21.62 \pm 0.03	0.64 \pm 0.06	119.31 \pm 3.53	29.81 \pm 2.42	89.50 \pm 1.12
	PB4	-4.52 \pm 0.03	-0.67 \pm 0.03	-0.55 \pm 0.06	-31.49 \pm 5.34	-21.68 \pm 2.20	-9.81 \pm 3.15
	PB5	-0.81 \pm 0.03	-5.85 \pm 0.03	-0.48 \pm 0.06	2.41 \pm 6.04	-4.40 \pm 0.87	6.81 \pm 5.17
Spring 2013-Spring 2014	PB1	3.36 \pm 0.03	0.96 \pm 0.03	0.21 \pm 0.06	8.90 \pm 3.00	4.21 \pm 1.41	4.69 \pm 1.59
	PB2	-2.24 \pm 0.03	7.77 \pm 0.03	0.44 \pm 0.06	1.21 \pm 3.70	6.37 \pm 2.77	-5.16 \pm 0.93
	PB3	-6.47 \pm 0.03	-1.64 \pm 0.03	0.87 \pm 0.06	-0.18 \pm 4.46	7.64 \pm 3.28	-7.82 \pm 1.19
	PB4	-3.77 \pm 0.03	-1.34 \pm 0.03	0.10 \pm 0.06	-0.05 \pm 5.11	4.86 \pm 2.07	-4.92 \pm 3.03
	PB5	0.80 \pm 0.03	-0.86 \pm 0.03	0.18 \pm 0.06	15.29 \pm 6.04	3.49 \pm 1.04	11.80 \pm 5.02
Spring 2014-Spring 2015	PB1	-0.45 \pm 0.03	0.54 \pm 0.03	0.31 \pm 0.06	2.63 \pm 3.08	1.99 \pm 1.54	0.64 \pm 1.54
	PB2	-0.51 \pm 0.03	-1.85 \pm 0.03	0.33 \pm 0.06	-2.06 \pm 3.62	0.88 \pm 2.60	-2.93 \pm 1.03
	PB3	-5.97 \pm 0.03	-0.04 \pm 0.03	0.00 \pm 0.06	-13.03 \pm 4.11	-0.98 \pm 3.23	-12.05 \pm 0.88
	PB4	-4.58 \pm 0.03	-5.87 \pm 0.03	0.47 \pm 0.06	-12.85 \pm 4.87	-1.79 \pm 1.95	-11.06 \pm 2.92
	PB5	6.23 \pm 0.03	1.21 \pm 0.03	-0.05 \pm 0.06	9.64 \pm 6.24	1.20 \pm 1.26	8.44 \pm 4.98
Spring 2015-Spring 2016	PB1	-0.57 \pm 0.03	0.09 \pm 0.03	0.12 \pm 0.06	0.27 \pm 3.05	0.64 \pm 1.61	-0.38 \pm 1.44
	PB2	1.63 \pm 0.03	0.07 \pm 0.03	0.12 \pm 0.06	0.65 \pm 3.65	-0.42 \pm 2.51	1.07 \pm 1.15
	PB3	-0.17 \pm 0.03	0.70 \pm 0.03	0.01 \pm 0.06	-6.66 \pm 3.93	-2.89 \pm 3.03	-3.77 \pm 0.91
	PB4	-3.82 \pm 0.03	2.42 \pm 0.03	-0.08 \pm 0.06	-8.62 \pm 4.63	-2.44 \pm 1.71	-6.18 \pm 2.92
	PB5	3.45 \pm 0.03	-0.44 \pm 0.03	-0.03 \pm 0.06	7.03 \pm 6.51	0.79 \pm 1.39	6.24 \pm 5.12
Spring 2016-Spring 2017	PB1	-0.22 \pm 0.03	0.03 \pm 0.03	0.01 \pm 0.06	-0.30 \pm 3.03	-0.82 \pm 1.74	0.53 \pm 1.29
	PB2	-2.88 \pm 0.03	0.22 \pm 0.03	0.02 \pm 0.06	-4.70 \pm 3.62	-0.29 \pm 2.44	-4.42 \pm 1.18
	PB3	-4.35 \pm 0.03	-0.46 \pm 0.03	-0.02 \pm 0.06	-3.10 \pm 3.80	1.05 \pm 2.89	-4.15 \pm 0.91
	PB4	-6.38 \pm 0.03	-0.49 \pm 0.03	0.08 \pm 0.06	-9.63 \pm 4.35	-1.91 \pm 1.50	-7.72 \pm 2.85
	PB5	1.10 \pm 0.03	0.38 \pm 0.03	0.02 \pm 0.06	1.67 \pm 6.64	0.45 \pm 1.46	1.22 \pm 5.18

5-year Topography Change

The Spring 2012 to Spring 2017 net change at Plumb Beach was dominated by the beach nourishment event that occurred in 2012. Profiles within the constructed fill (PB2 and PB3) gained cross-section area, elevation of foredune crest and distance to foredune crest and intersection with NAVD88 were all displaced seaward (Table 18 and Figure 59). PB1 to the west of the fill was relatively stable, with some gain in elevation of foredune crest. PB4, downdrift of the stone groin to the east, lost cross-section area and the foredune crest was displaced inland as well as the intersection with NAVD88. PB5 gained cross-section area, perhaps due to the erosion of PB4 updrift.

Table 18. Net change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Plumb Beach, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012-Spring 2017	PB1	1.37 \pm 0.03	1.74 \pm 0.03	0.65 \pm 0.06	4.49 \pm 2.98	3.14 \pm 1.66	1.35 \pm 1.34
	PB2	42.25 \pm 0.03	25.36 \pm 0.03	1.83 \pm 0.06	121.19 \pm 2.63	47.15 \pm 1.73	74.05 \pm 0.92
	PB3	32.46 \pm 0.03	20.18 \pm 0.03	1.49 \pm 0.06	96.34 \pm 2.91	34.62 \pm 2.16	61.71 \pm 0.78
	PB4	-23.07 \pm 0.03	-5.94 \pm 0.03	0.03 \pm 0.06	-62.65 \pm 4.86	-22.97 \pm 1.91	-39.67 \pm 2.97
	PB5	10.76 \pm 0.03	-5.55 \pm 0.03	-0.35 \pm 0.06	36.04 \pm 6.37	1.53 \pm 1.22	34.50 \pm 5.18

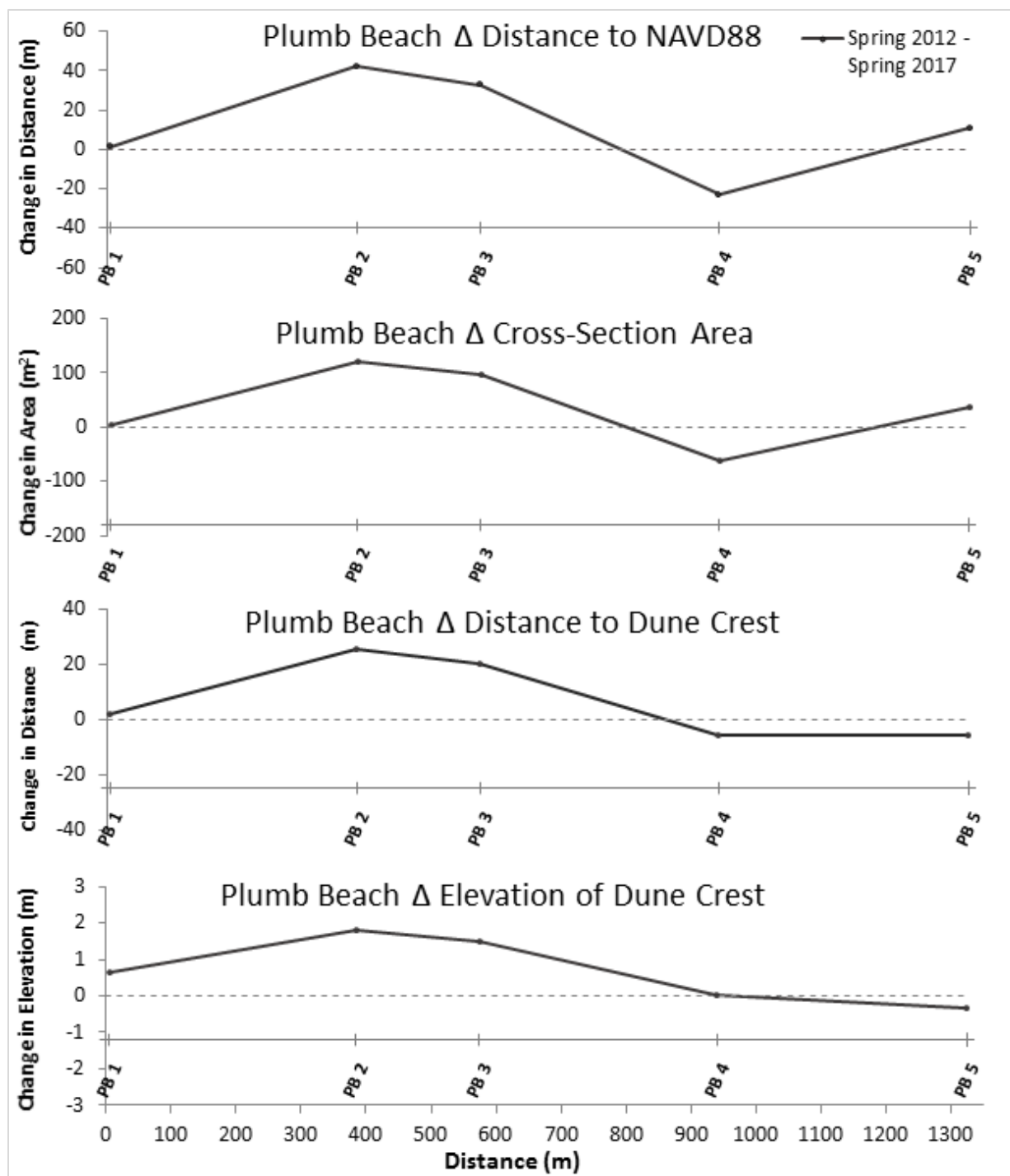


Figure 59. Alongshore dimensions of selected topographical variables at Plumb Beach within the Jamaica Bay Unit, Gateway National Recreation Area, from Spring 2012 – Spring 2017, incorporating dune/beach profile.

Staten Island Unit

Great Kills

Great Kills is located along the Staten Island shoreline and is exposed to ocean waves entering Raritan Bay and generating nearshore currents and transport to the southwest (Figure 60). The dominant sediment transport direction is to the southwest. An outfall pipe at the northeastern margin of the park serves as a large groin that effectively limits sediment input from updrift and creates a negative sediment budget in this portion of the park. Great Kills is composed of three major topographical segments: 1) an area of fill to the northeast that comprises a planar surface approximately 3-4 m in elevation and fronted by a low bluff and narrow beach; 2) an area incorporating an anthropogenic dune-ridge northeast of the Bath House as well as natural beach and dune topography to the southwest consisting of an active beach-dune system; and 3) the more sheltered bayside, downdrift of the jetty. The navigation channel next to the southwestern node of Great Kills is periodically dredged, and in 2014 sediment was removed from the protruding node as well as from the channel (Table 2, Figure 60). A detailed report of the geomorphology of Great Kills is available (Psuty et al. 2015a; Psuty et al. 2017b). Nine monuments have been established along the ocean-facing shoreline of Great Kills (Figure 60). The location, description, and coordinates of the Great Kills monuments are detailed in a booklet prepared for this purpose (Psuty et al. 2010d).

Profile data are missing for GK5 in Spring 2013 due to a malfunction in the radio antenna during the survey, the Fall 2013 survey was used instead.



Figure 60. Site of coastal topography profiles at Great Kills within the Staten Island Unit, Gateway National Recreation Area. Note the dredging and sediment removal at the southwestern tip of Great Kills.

Annual Topography Change

Profiles GK1 – GK4, located in the bluff portion of Great Kills, were heavily eroded during Hurricane Sandy in 2012 (Figure 61 and Figure 62). The bluff edge was displaced inland -1.5 m to -20 m, and these profiles all lost cross-section area (Table 19). Post-storm, the bluff profiles have continued to erode, though at a lesser rate than the storm induced erosion. Profiles lost beach cross-section area, bluff cross-section area, and the bluff edge was displaced inland annually.

To the southeast, profiles within the area of dune topography along Great Kills (GK5 – GK6) were also impacted by Hurricane Sandy (Figure 63). The foredune crest location was displaced inland -1.4 m to -36 m, and profile GK6 lost total cross-section area. GK5, however, gained area in both the dune and beach feature. The gain in the dune area was due to washover from the eliminated foredune, and the beach area may have been fed by erosion updrift. It is also important to note that the GK5 comparison of pre and post-storm is from Spring 2012 to Fall 2013, thus having more time to recover than other profiles. Post-storm, the beach and dune areas along profile GK5 were relatively stable. GK6 consistently gained cross-section area in the beach and dune.

The profiles along Great Kills Bayside were more sheltered from the effects of Hurricane Sandy. Though both were eroded in the beach and dune feature post-storm, it was to a lesser extent than the more exposed oceanside profiles (Figure 64 and Figure 65). The foredune crest location was displaced inland -1.4 m to -8 m, and all profiles lost cross-section area. Both GK7 and GK8, after an initial recovery of area in 2014, continued to erode to the Spring 2017 survey. Profile GK9.1 eroded continuously in the dune and beach features, with the exception of the Spring 2014 survey. The Spring 2014 survey was the first survey conducted after the dredging of the Great Kills channel in the winter of 2014. Perhaps mobilization of sediment due to the dredging and sediment removal from the projecting accumulation caused the gain in GK9.1 during this period. GK9.2 was generally accretional post-storm, fed by the erosion of GK9.1 updrift. Again, the Spring 2014 survey, after the dredging event, was notably different than the other five spring surveys. There was a loss of -15 m² of cross-section area.

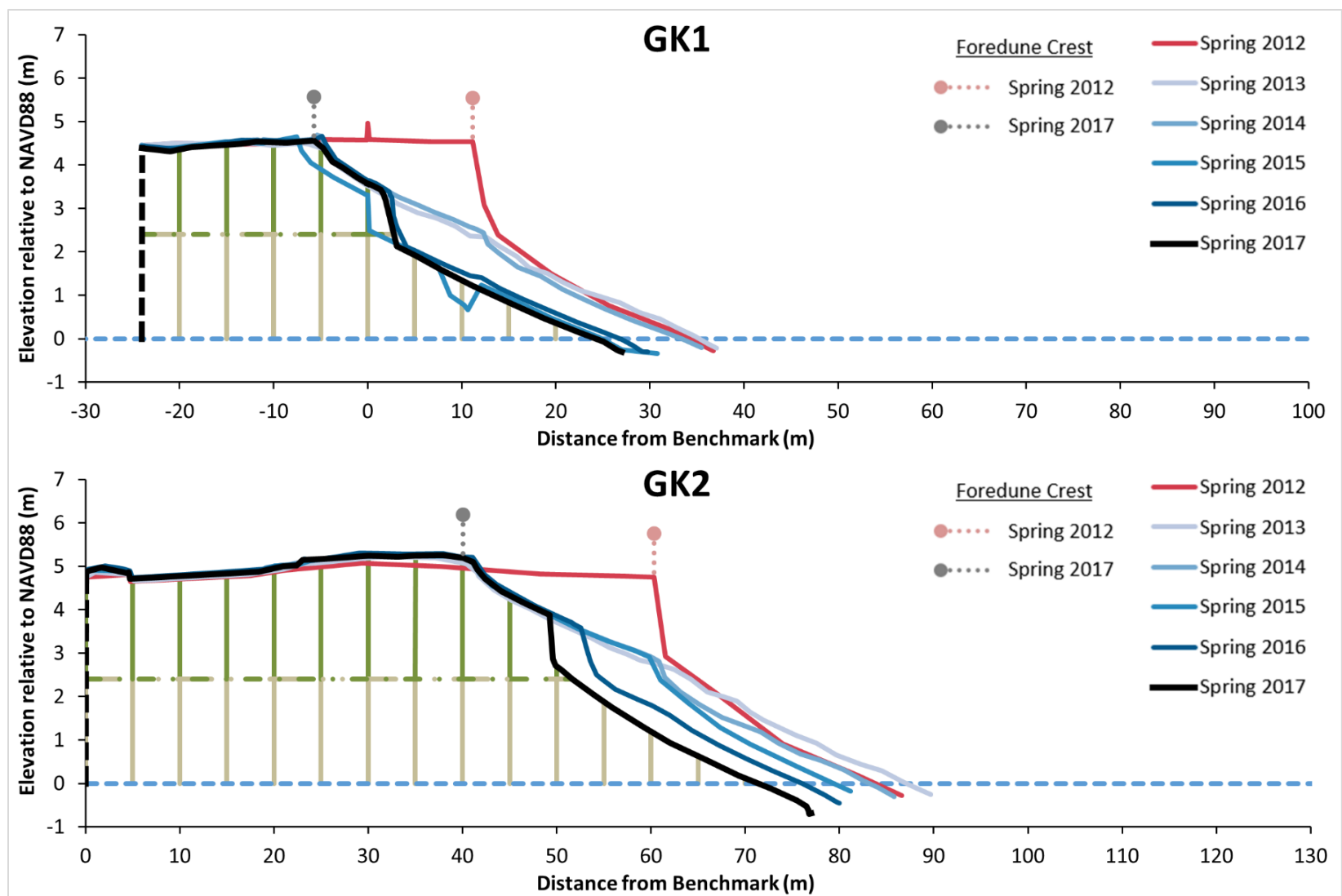


Figure 61. Coastal topography of Profiles GK1 and GK2 along the oceanside of Great Kills within the Staten Island Unit, Gateway National Recreation Area. Bluff edge location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

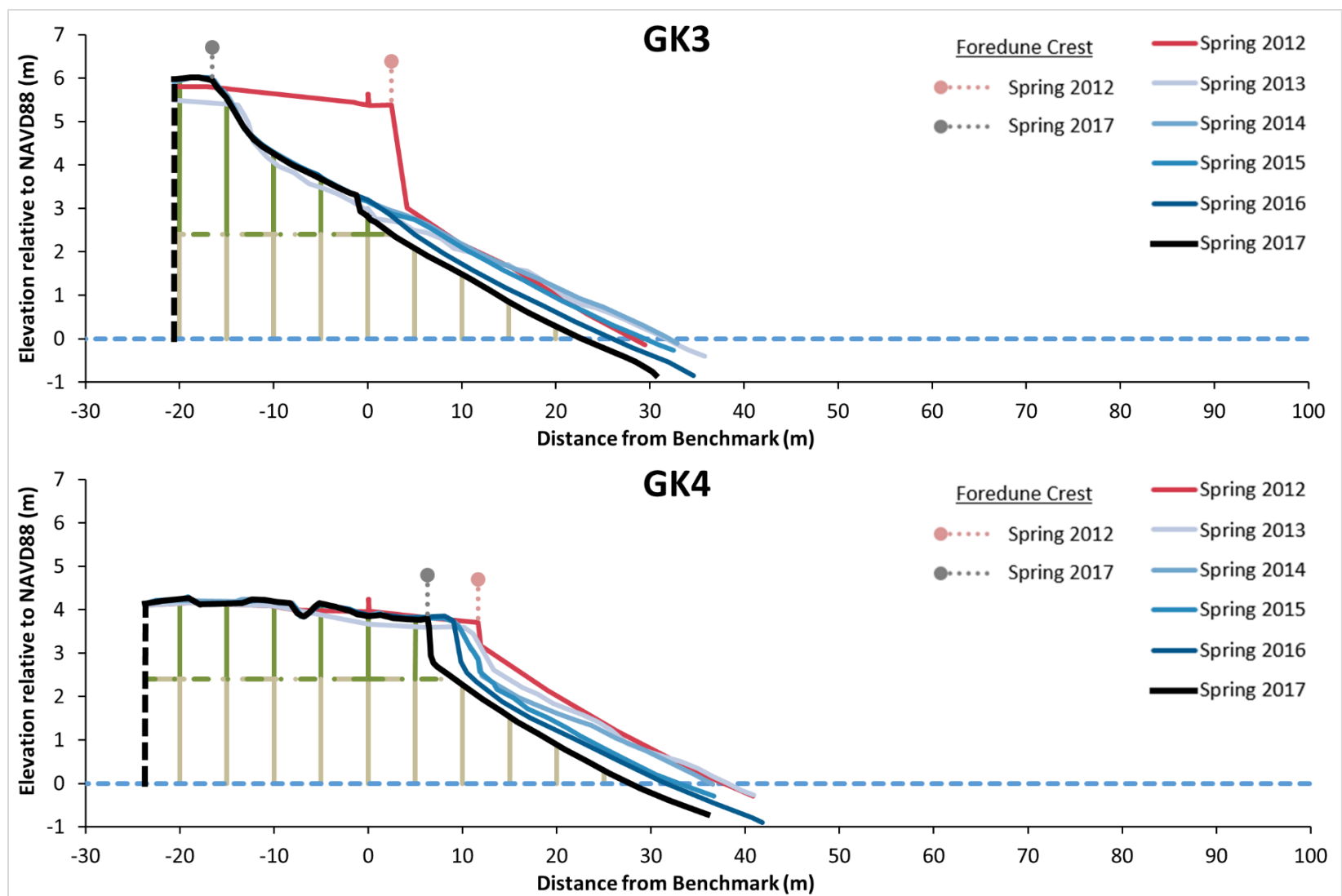


Figure 62. Coastal topography of Profiles GK3 and GK4 along the oceanside of Great Kills within the Staten Island Unit, Gateway National Recreation Area. Bluff edge location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

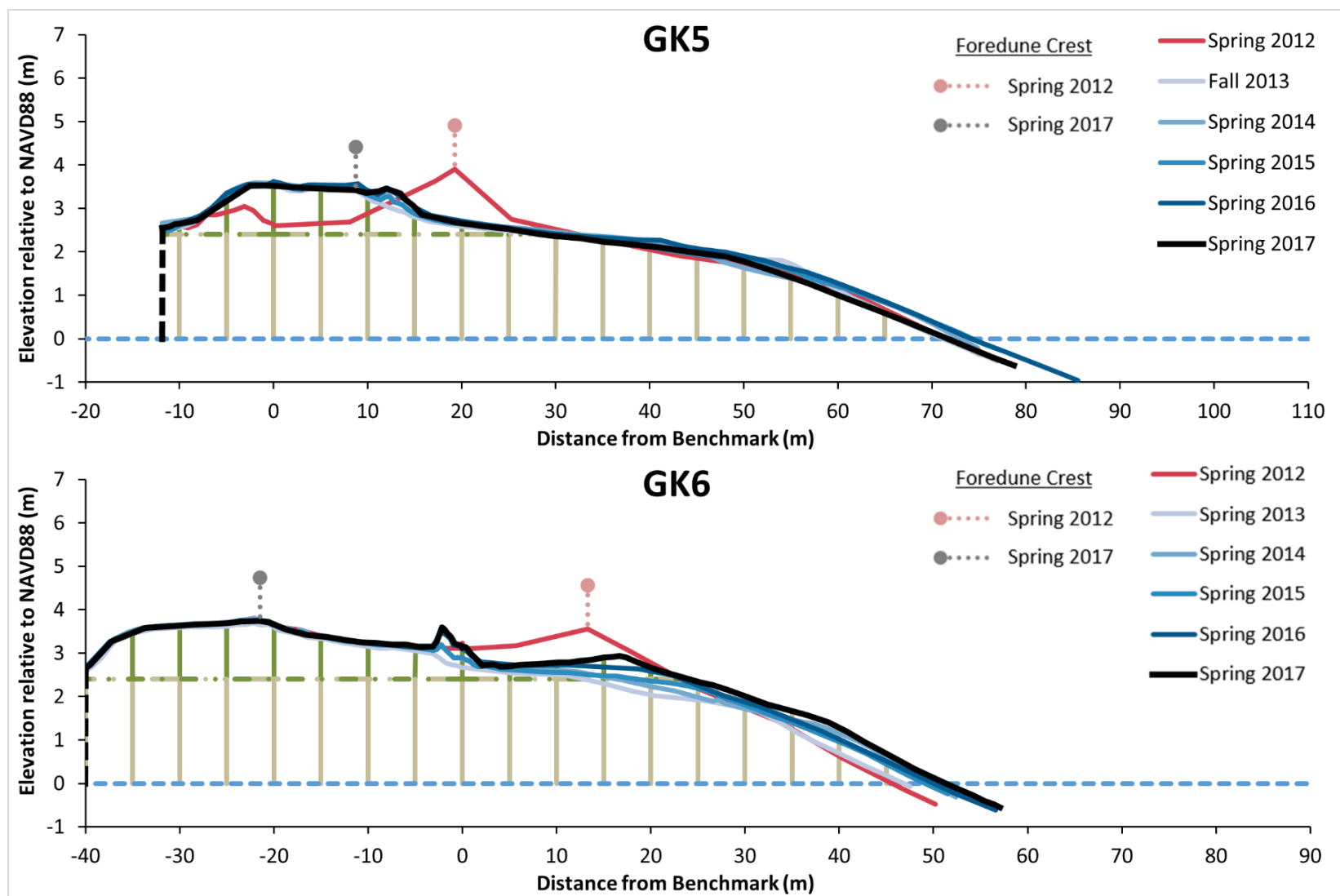


Figure 63. Coastal topography of Profiles GK5 and GK6 along the oceanside of Great Kills within the Staten Island Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

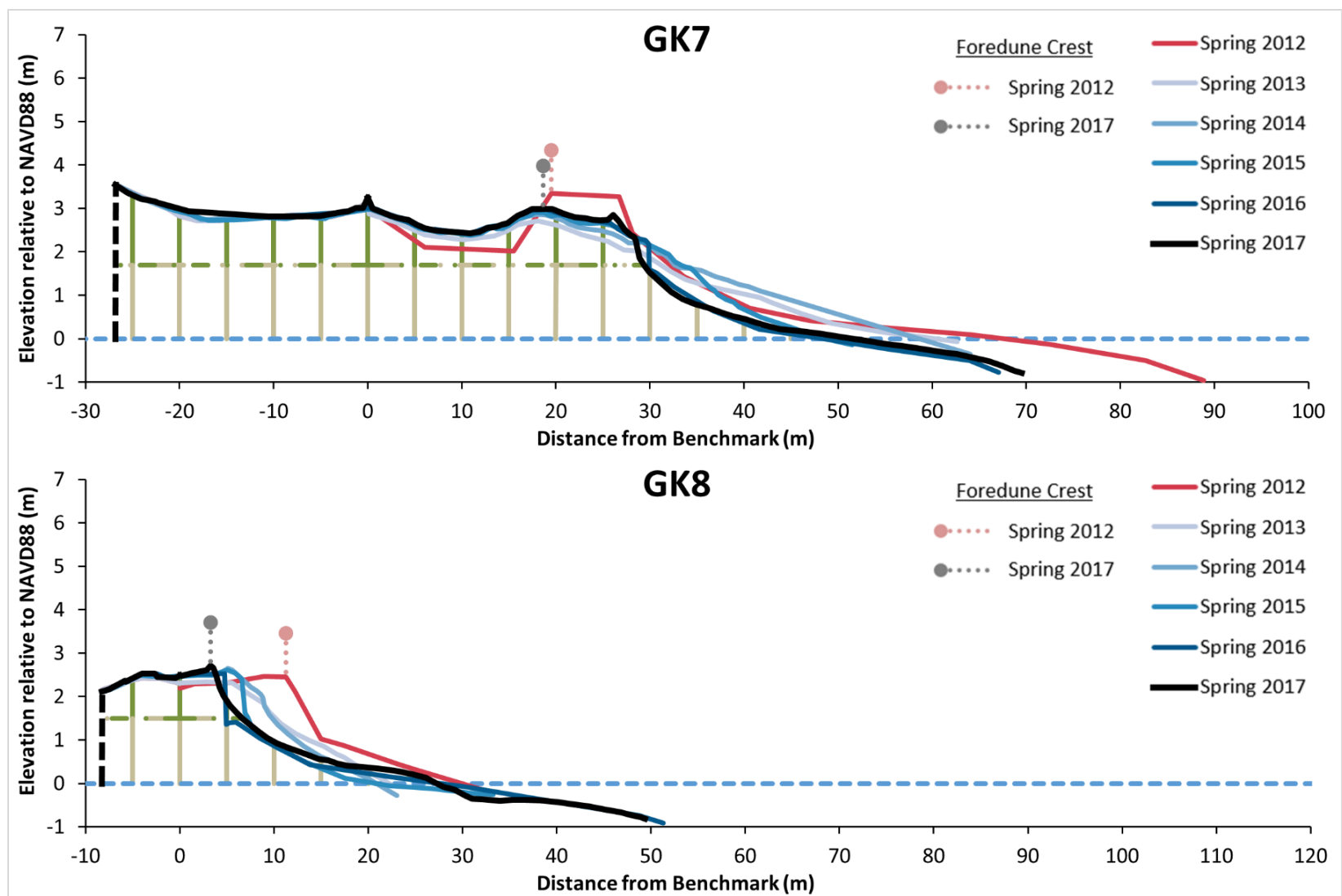


Figure 64. Coastal topography of Profiles GK7 and GK8 along the bayside of Great Kills within the Staten Island Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

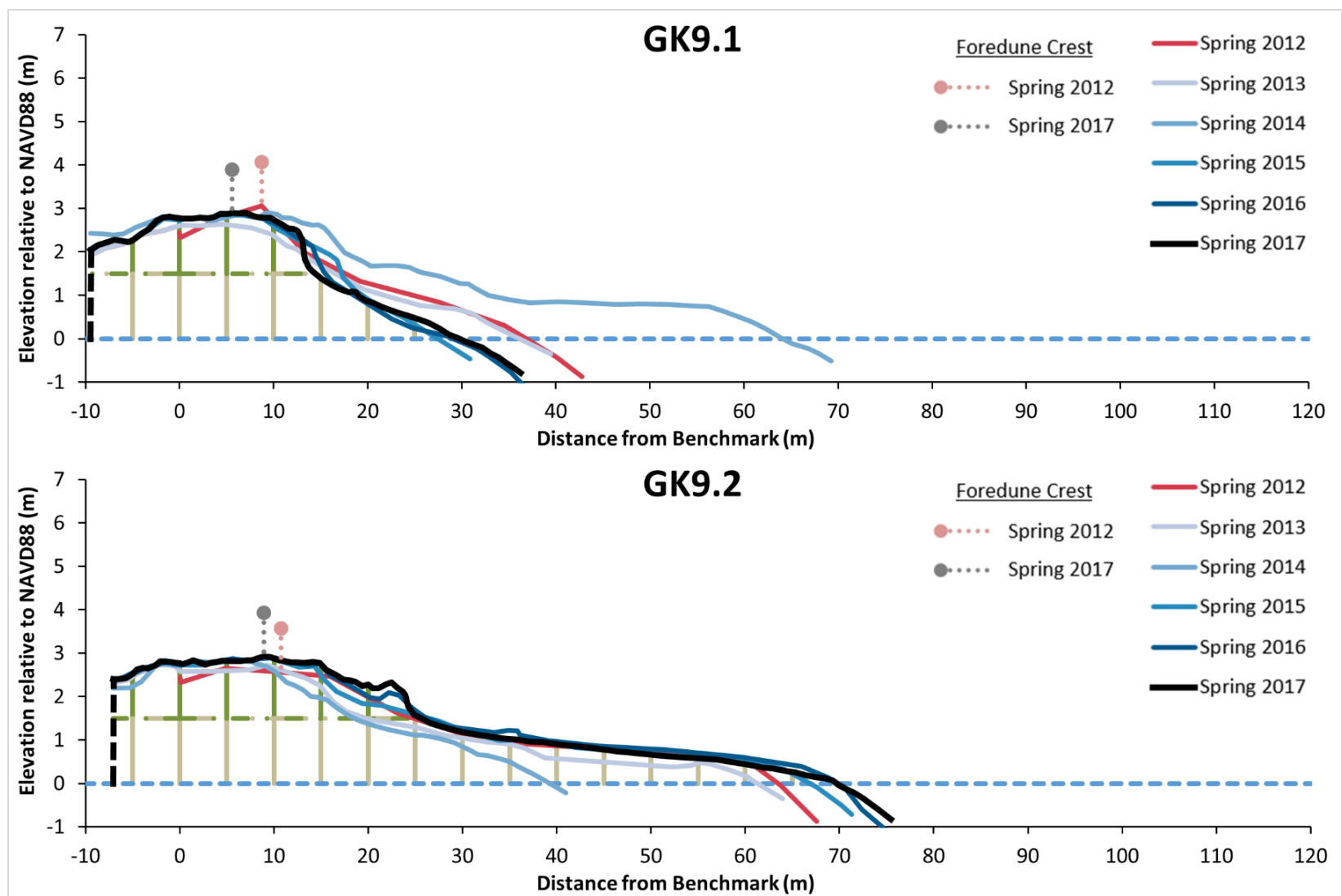


Figure 65. Coastal topography of Profiles GK9.1 and GK9.2 along the bayside of Great Kills within the Staten Island Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

Table 19. Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Great Kills, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest / Cliff Edge	Foredune Crest / Cliff Edge	Total	Dune / Cliff	Beach
Spring 2012- Spring 2013	GK1	0.98 ± 0.03	-17.35 ± 0.03	-0.06 ± 0.06	-24.12 ± 3.32	-24.03 ± 2.05	-0.08 ± 1.28
	GK2	3.32 ± 0.03	-19.96 ± 0.03	0.31 ± 0.06	-16.12 ± 4.84	-20.68 ± 3.65	4.56 ± 1.19
	GK3	3.50 ± 0.03	-16.29 ± 0.03	0.00 ± 0.06	-34.56 ± 2.86	-36.84 ± 1.59	2.28 ± 1.28
	GK4	0.41 ± 0.03	-1.49 ± 0.03	-0.11 ± 0.06	-6.89 ± 3.49	-5.00 ± 2.25	-1.90 ± 1.24
	GK5*	-0.32 ± 0.03	-18.84 ± 0.03	-0.39 ± 0.06	3.01 ± 4.71	0.20 ± 2.43	2.81 ± 2.28
	GK6	1.21 ± 0.03	-35.54 ± 0.03	0.14 ± 0.06	-22.58 ± 4.88	-19.46 ± 3.30	-3.12 ± 1.63
	GK7	-7.22 ± 0.03	-1.42 ± 0.03	-0.63 ± 0.06	-4.89 ± 5.14	-5.24 ± 3.31	0.35 ± 1.84
	GK8	-7.66 ± 0.03	-8.43 ± 0.03	-0.12 ± 0.06	-10.01 ± 1.96	-4.22 ± 1.15	-5.80 ± 0.81
	GK9.1	-0.70 ± 0.03	-4.07 ± 0.03	-0.42 ± 0.06	-5.27 ± 2.60	-2.98 ± 1.50	-2.29 ± 1.10
	GK9.2	-2.14 ± 0.03	-1.45 ± 0.03	0.16 ± 0.06	-11.98 ± 3.93	-3.26 ± 1.67	-8.73 ± 2.27
Spring 2013- Spring 2014	GK1	-1.80 ± 0.03	0.85 ± 0.03	0.21 ± 0.06	-1.55 ± 3.30	2.75 ± 2.01	-4.30 ± 1.29
	GK2	-3.99 ± 0.03	0.82 ± 0.03	0.06 ± 0.06	-3.34 ± 4.82	5.22 ± 3.56	-8.57 ± 1.26
	GK3	0.29 ± 0.03	-2.47 ± 0.03	0.56 ± 0.06	8.24 ± 2.97	6.79 ± 1.59	1.45 ± 1.38
	GK4	-1.80 ± 0.03	-1.20 ± 0.03	0.16 ± 0.06	-0.45 ± 3.45	3.14 ± 2.12	-3.59 ± 1.33
	GK5*	1.84 ± 0.03	7.83 ± 0.03	-0.01 ± 0.06	5.37 ± 4.75	4.42 ± 2.43	0.95 ± 2.32
	GK6	3.02 ± 0.03	0.21 ± 0.03	0.11 ± 0.06	13.11 ± 5.00	5.42 ± 3.10	7.69 ± 1.90
	GK7	-1.73 ± 0.03	-0.22 ± 0.03	0.14 ± 0.06	10.72 ± 4.89	5.62 ± 3.32	5.09 ± 1.57
	GK8	-1.41 ± 0.03	2.25 ± 0.03	0.31 ± 0.06	-0.02 ± 1.69	2.11 ± 1.03	-2.13 ± 0.65
	GK9.1	27.98 ± 0.03	1.17 ± 0.03	0.20 ± 0.06	42.76 ± 3.46	12.09 ± 1.77	30.67 ± 1.70
	GK9.2	-22.12 ± 0.03	-3.08 ± 0.03	0.13 ± 0.06	-15.19 ± 3.30	-0.58 ± 1.48	-14.60 ± 1.86
Spring 2014- Spring 2015	GK1	-8.52 ± 0.03	-2.22 ± 0.03	-0.04 ± 0.06	-32.93 ± 3.02	-10.84 ± 1.77	-22.09 ± 1.27
	GK2	-3.75 ± 0.03	-0.42 ± 0.03	0.04 ± 0.06	-7.56 ± 4.60	-1.53 ± 3.47	-6.03 ± 1.13
	GK3	-2.59 ± 0.03	-0.63 ± 0.03	0.07 ± 0.06	-5.12 ± 2.90	-0.45 ± 1.62	-4.67 ± 1.29
	GK4	-3.43 ± 0.03	-0.97 ± 0.03	0.05 ± 0.06	-6.88 ± 3.30	-0.47 ± 2.06	-6.40 ± 1.25
	GK5	1.29 ± 0.03	-1.31 ± 0.03	-0.04 ± 0.06	-0.82 ± 4.84	-2.13 ± 2.45	0.69 ± 2.39
	GK6	-0.75 ± 0.03	0.37 ± 0.03	-0.05 ± 0.06	-1.30 ± 5.06	-0.86 ± 3.25	-0.45 ± 1.81

* Spring 2013 survey not collected, comparison with Fall 2013

Table 19 (continued). Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Great Kills, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest / Cliff Edge	Foredune Crest / Cliff Edge	Total	Dune / Cliff	Beach
Spring 2014- Spring 2015 (cont.)	GK7	-9.90 \pm 0.03	-0.07 \pm 0.03	0.06 \pm 0.06	-9.99 \pm 4.57	0.51 \pm 3.38	-10.50 \pm 1.21
	GK8	0.02 \pm 0.03	-0.10 \pm 0.03	-0.04 \pm 0.06	-5.92 \pm 1.65	-1.72 \pm 0.95	-4.20 \pm 0.70
	GK9.1	-36.68 \pm 0.03	0.80 \pm 0.03	0.03 \pm 0.06	-44.52 \pm 3.29	-6.65 \pm 1.79	-37.87 \pm 1.57
	GK9.2	27.66 \pm 0.03	3.43 \pm 0.03	0.03 \pm 0.06	32.08 \pm 3.49	6.80 \pm 1.69	25.28 \pm 1.82
Spring 2015- Spring 2016	GK1	1.94 \pm 0.03	0.27 \pm 0.03	-0.10 \pm 0.06	11.49 \pm 2.82	6.45 \pm 1.49	5.04 \pm 1.34
	GK2	-3.35 \pm 0.03	0.31 \pm 0.03	0.05 \pm 0.06	-12.69 \pm 4.40	-2.95 \pm 3.28	-9.74 \pm 1.12
	GK3	-3.39 \pm 0.03	0.02 \pm 0.03	-0.01 \pm 0.06	-8.72 \pm 2.74	-1.05 \pm 1.53	-7.67 \pm 1.21
	GK4	-1.38 \pm 0.03	0.11 \pm 0.03	0.05 \pm 0.06	-4.79 \pm 3.17	-1.51 \pm 2.02	-3.28 \pm 1.15
	GK5	-0.12 \pm 0.03	2.03 \pm 0.03	0.10 \pm 0.06	5.15 \pm 4.87	2.93 \pm 2.40	2.84 \pm 2.47
	GK6	0.95 \pm 0.03	-0.03 \pm 0.03	-0.01 \pm 0.06	6.76 \pm 5.07	4.60 \pm 3.45	2.17 \pm 1.62
	GK7	-0.33 \pm 0.03	1.25 \pm 0.03	0.06 \pm 0.06	-3.62 \pm 4.27	2.31 \pm 3.31	-5.93 \pm 0.97
	GK8	6.74 \pm 0.03	-0.28 \pm 0.03	-0.09 \pm 0.06	-0.73 \pm 1.85	-1.83 \pm 0.82	1.10 \pm 1.06
	GK9.1	1.64 \pm 0.03	-0.97 \pm 0.03	0.02 \pm 0.06	-1.74 \pm 2.13	-0.39 \pm 1.46	-1.35 \pm 0.68
	GK9.2	3.00 \pm 0.03	0.16 \pm 0.03	0.02 \pm 0.06	7.73 \pm 4.27	3.06 \pm 1.89	4.68 \pm 2.38
Spring 2016- Spring 2017	GK1	-2.56 \pm 0.03	1.56 \pm 0.03	0.02 \pm 0.06	-6.88 \pm 2.81	-2.18 \pm 1.54	-4.70 \pm 1.27
	GK2	-4.70 \pm 0.03	-1.03 \pm 0.03	-0.02 \pm 0.06	-17.53 \pm 4.17	-7.06 \pm 3.01	-10.47 \pm 1.16
	GK3	-3.25 \pm 0.03	0.33 \pm 0.03	-0.05 \pm 0.06	-8.27 \pm 2.55	-2.25 \pm 1.38	-6.02 \pm 1.17
	GK4	-3.80 \pm 0.03	-1.83 \pm 0.03	-0.06 \pm 0.06	-10.54 \pm 3.02	-4.17 \pm 1.92	-6.37 \pm 1.10
	GK5	-2.45 \pm 0.03	-0.23 \pm 0.03	-0.15 \pm 0.06	-9.52 \pm 4.80	-2.08 \pm 2.35	-7.44 \pm 2.45
	GK6	1.22 \pm 0.03	0.22 \pm 0.03	0.00 \pm 0.06	6.72 \pm 5.13	2.05 \pm 3.61	4.67 \pm 1.52
	GK7	3.15 \pm 0.03	-0.40 \pm 0.03	0.01 \pm 0.06	0.15 \pm 4.35	-0.21 \pm 3.20	0.36 \pm 1.16
	GK8	-0.36 \pm 0.03	-1.48 \pm 0.03	0.19 \pm 0.06	3.22 \pm 2.02	0.28 \pm 0.80	2.94 \pm 1.23
	GK9.1	0.66 \pm 0.03	-0.08 \pm 0.03	0.01 \pm 0.06	0.86 \pm 2.20	-0.52 \pm 1.38	1.38 \pm 0.82
	GK9.2	-0.18 \pm 0.03	-0.85 \pm 0.03	0.02 \pm 0.06	-3.49 \pm 4.35	1.41 \pm 1.87	-4.90 \pm 2.48

5-year Topography Change

From Spring 2012 to Spring 2017, the profiles along the bluff area in Great Kills have lost an average of -47 m^2 in each of Profiles GK1 – GK4, equally divided into loss from the beach feature and bluff feature (Table 20). Loss in cross-section area was greatest in the northeastern portion of Great Kills and diminished to the southwest to result in more stable profiles (Figure 66). Profiles along the bayside also lost cross-section area, though of a lesser magnitude compared to the oceanside. Along all profiles, the foredune crest/bluff edge was displaced inland.

Table 20. Net change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Great Kills, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest / Cliff Edge	Foredune Crest / Cliff Edge	Total	Dune / Cliff	Beach
Spring 2012- Spring 2017	GK1	-9.96 \pm 0.03	-16.89 \pm 0.03	0.02 \pm 0.06	-53.99 \pm 3.03	-27.85 \pm 1.86	-26.13 \pm 1.18
	GK2	-12.47 \pm 0.03	-20.27 \pm 0.03	0.44 \pm 0.06	-57.24 \pm 4.40	-27.00 \pm 3.32	-30.25 \pm 1.09
	GK3	-5.43 \pm 0.03	-19.05 \pm 0.03	0.57 \pm 0.06	-48.44 \pm 2.61	-33.81 \pm 1.49	-14.63 \pm 1.13
	GK4	-10.00 \pm 0.03	-5.37 \pm 0.03	0.09 \pm 0.06	-29.55 \pm 3.21	-8.01 \pm 2.10	-21.54 \pm 1.11
	GK5	0.24 \pm 0.03	-10.51 \pm 0.03	-0.49 \pm 0.06	3.19 \pm 4.72	3.35 \pm 2.40	-0.16 \pm 2.32
	GK6	5.64 \pm 0.03	-34.77 \pm 0.03	0.18 \pm 0.06	2.70 \pm 5.01	-8.25 \pm 3.60	10.95 \pm 1.41
	GK7	-16.04 \pm 0.03	-0.86 \pm 0.03	-0.37 \pm 0.06	-7.64 \pm 4.91	2.99 \pm 3.26	-10.62 \pm 1.68
	GK8	-2.67 \pm 0.03	-8.03 \pm 0.03	0.25 \pm 0.06	-13.46 \pm 2.09	-5.37 \pm 1.06	-8.09 \pm 1.05
	GK9.1	-7.11 \pm 0.03	-3.15 \pm 0.03	-0.16 \pm 0.06	-7.91 \pm 2.43	1.55 \pm 1.44	-9.46 \pm 0.98
	GK9.2	6.22 \pm 0.03	-1.79 \pm 0.03	0.36 \pm 0.06	9.15 \pm 4.17	7.43 \pm 1.83	1.72 \pm 2.35

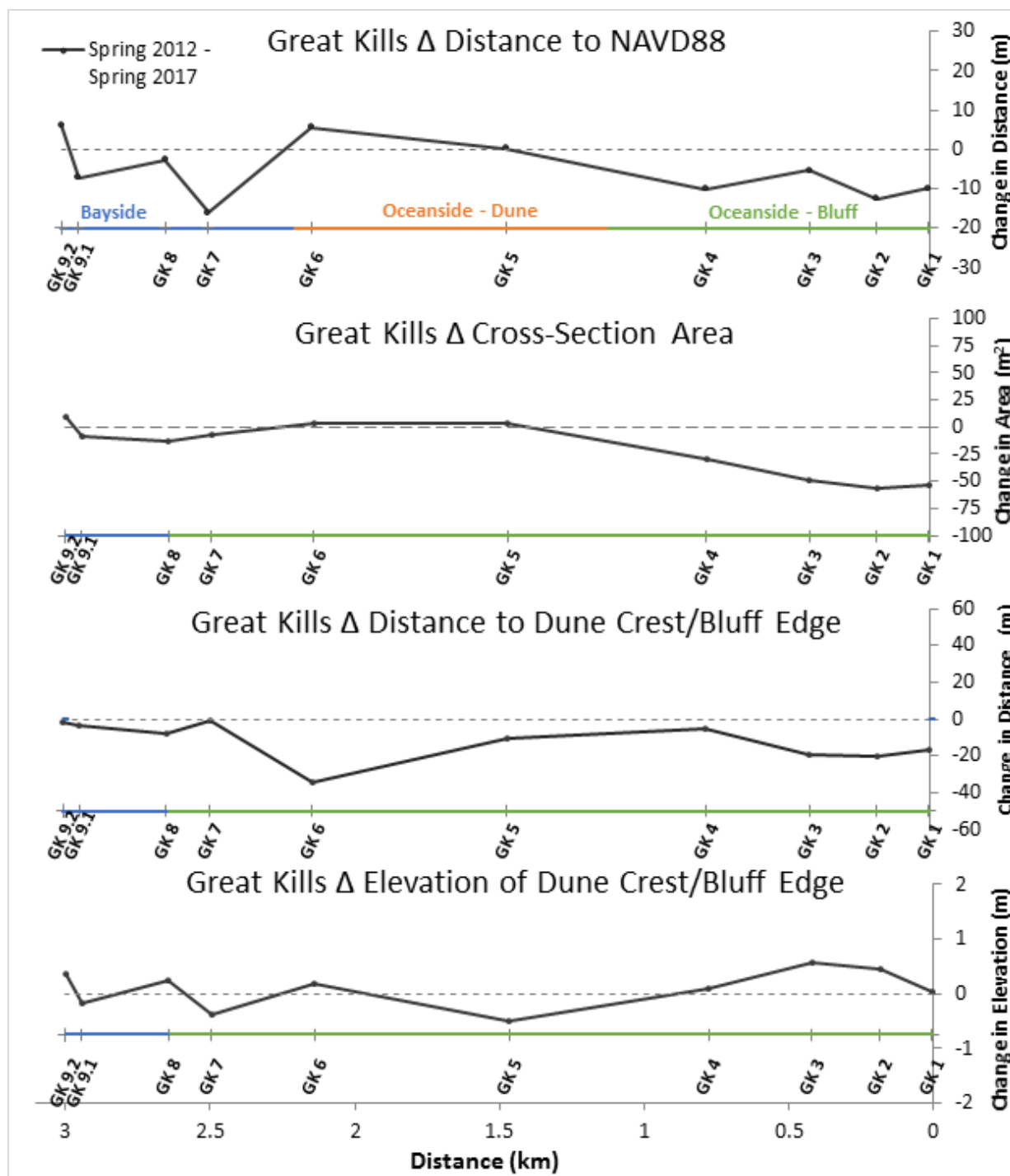


Figure 66. Alongshore dimensions of selected topographical variables at Great Kills Park within the Staten Island Unit, Gateway National Recreation Area, from Spring 2012 – Spring 2017, incorporating dune/beach profile sites along the oceanside and bayside of the site.

Miller Field

Miller Field is located along Staten Island in the sheltered Lower Bay and is bounded by two stone groins. There is a continuous foredune along the site, with breaks in the dune for beach access. The sediment transport direction is variable, either from the northeast or southwest. A detailed report of the geomorphology of Miller Field is available (Psuty et al. 2015a; Psuty et al. 2017b). Two monuments have been established along the ocean-facing of shoreline of Miller Field (Figure 67). The location, description, and coordinates of the Miller Field monuments are detailed in a booklet prepared for this purpose (Psuty et al. 2010e).



Figure 67. Sites of coastal topography profiles at Miller Field within the Staten Island Unit, Gateway National Recreation Area.

Annual Topography Change

The foredune on MF1 was eliminated during Hurricane Sandy, and the new location in 2013 was -21 m inland (Figure 68, Table 21). Hurricane Sandy also led to loss in the cross-section area of the beach and dune feature on MF1. MF2, however, gained cross-section area in the dune feature as washover, and the foredune crest moved seaward +40 m. This large seaward shift in the foredune crest was due to the anthropogenic manipulation of sediment during post-storm clean up and berm construction. The manipulated sediment formed a new artificial berm that was subsequently vegetated. Post-storm both profiles have been relatively stable with small changes in cross-section area in the beach and dune feature. The new foredune crest location on MF2 was also stable post-storm.

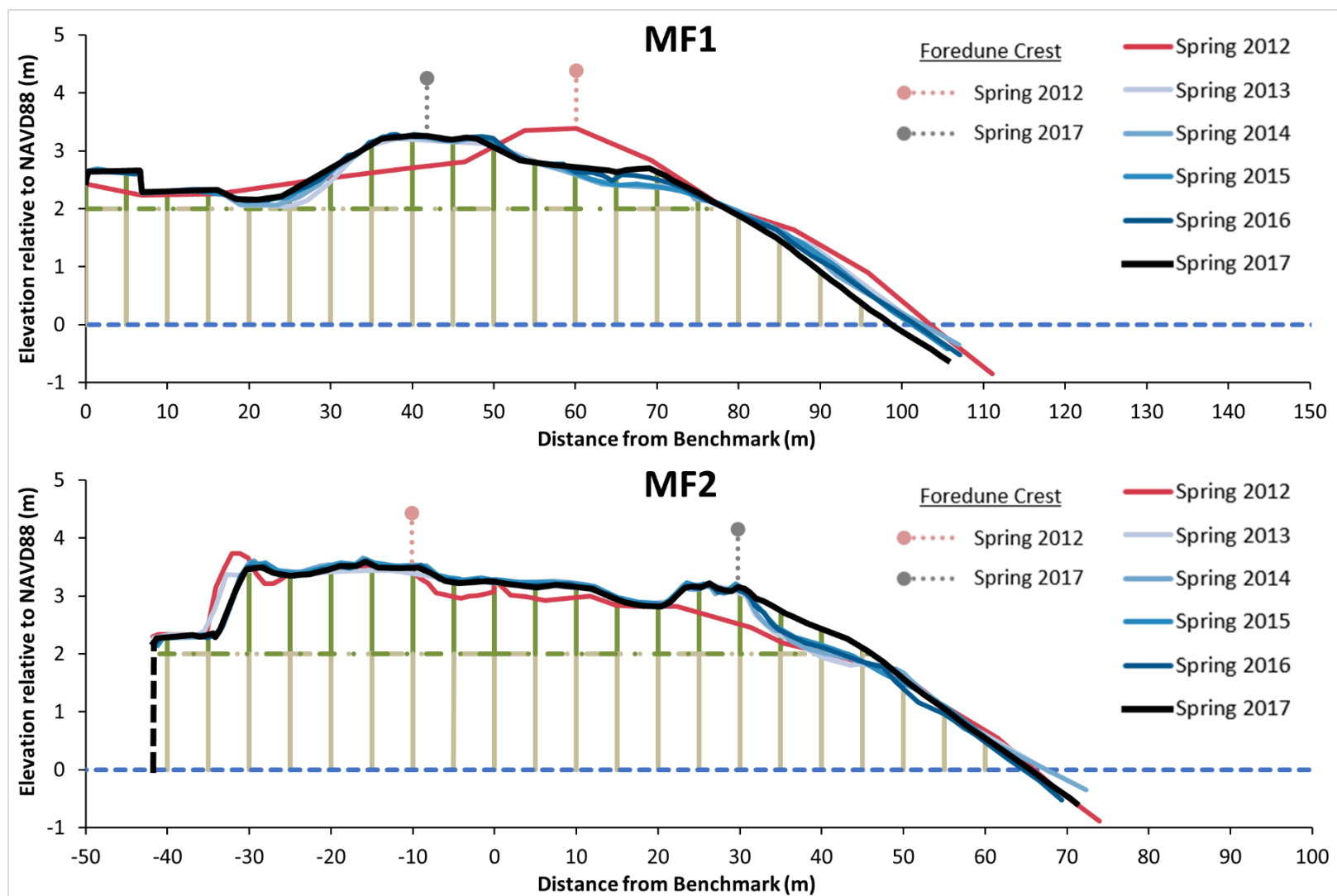


Figure 68. Coastal topography of Profiles MF1 and MF2 at Miller Field within the Staten Island Unit, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

Table 21. Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Miller Field, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012- Spring 2013	MF1	-1.49 ± 0.03	-21.98 ± 0.03	-0.17 ± 0.06	-10.20 ± 5.81	-6.50 ± 4.45	-3.70 ± 1.36
	MF2	1.38 ± 0.03	39.08 ± 0.03	-0.31 ± 0.06	8.01 ± 6.14	9.23 ± 4.63	-1.23 ± 1.51
Spring 2013- Spring 2014	MF1	0.53 ± 0.03	2.08 ± 0.03	0.05 ± 0.06	0.27 ± 5.79	1.26 ± 4.47	-0.99 ± 1.32
	MF2	0.07 ± 0.03	0.64 ± 0.03	-0.01 ± 0.06	0.52 ± 6.17	0.23 ± 4.62	0.29 ± 1.56
Spring 2014- Spring 2015	MF1	-1.30 ± 0.03	2.30 ± 0.03	-0.03 ± 0.06	2.15 ± 5.76	1.99 ± 4.48	0.16 ± 1.28
	MF2	-2.16 ± 0.03	-0.08 ± 0.03	0.10 ± 0.06	1.62 ± 6.11	2.30 ± 4.72	-0.68 ± 1.40
Spring 2015- Spring 2016	MF1	0.48 ± 0.03	-0.33 ± 0.03	0.02 ± 0.06	1.53 ± 5.74	2.19 ± 4.46	-0.67 ± 1.28
	MF2	-0.59 ± 0.03	-0.11 ± 0.03	-0.09 ± 0.06	-4.76 ± 6.04	-3.07 ± 4.77	-1.70 ± 1.26
Spring 2016- Spring 2017	MF1	-2.96 ± 0.03	-0.39 ± 0.03	0.01 ± 0.06	-2.38 ± 5.67	1.30 ± 4.44	-3.68 ± 1.23
	MF2	0.81 ± 0.03	0.37 ± 0.03	0.03 ± 0.06	6.21 ± 6.04	3.75 ± 4.86	2.47 ± 1.18

5-year Topography Change

From Spring 2012 to Spring 2017, MF1 eroded, losing cross-section area, and both the foredune crest and intersection with NAVD88 were displaced inland (Table 22 and Figure 69). MF2 however, gained cross-section area and both the distance to the foredune crest and intersection with NAVD88 was displaced seaward. The erosion of MF1 and accretion of MF2 indicated the dominant sediment transport direction was to the southwest during the survey period. The sediment lost from MF1 moved downdrift and led to accretion on MF2.

Table 22. Net change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Miller Field, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012-	MF1	-4.75 \pm 0.03	-18.32 \pm 0.03	-0.13 \pm 0.06	-8.64 \pm 5.72	0.24 \pm 4.45	-8.88 \pm 1.28
Spring 2017	MF2	-0.49 \pm 0.03	39.90 \pm 0.03	-0.27 \pm 0.06	11.60 \pm 6.08	12.44 \pm 4.82	-0.84 \pm 1.27

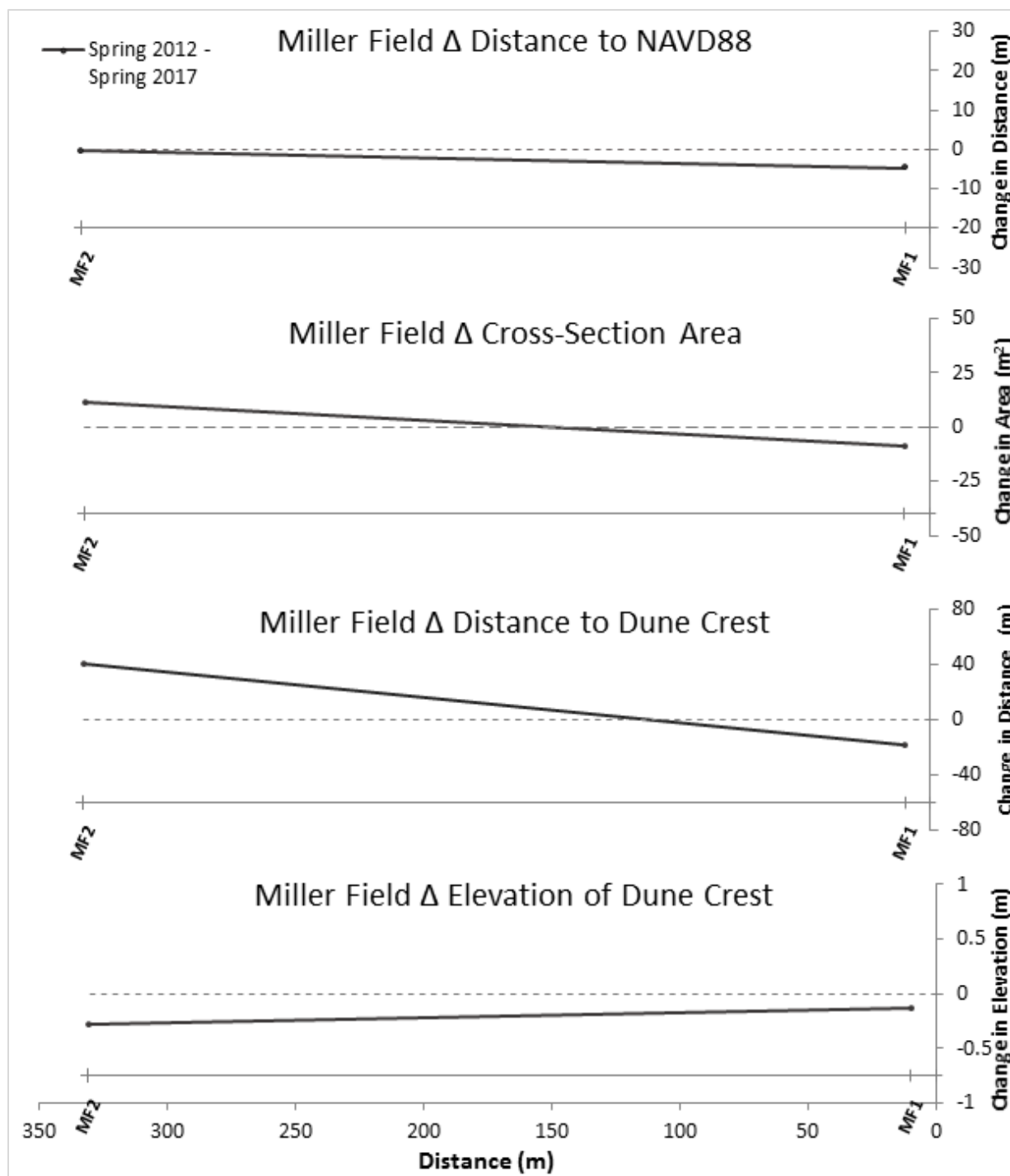


Figure 69. Alongshore dimensions of selected topographical variables at Miller Field within the Staten Island Unit, Gateway National Recreation Area, from Spring 2012 – Spring 2017, incorporating dune/beach profile sites along the western, southern and northwestern areas.

Fort Wadsworth

Fort Wadsworth is the northeasternmost park within the Staten Island Unit. It is located in the relatively sheltered Lower Bay and is bounded by a large stone jetty to the northeast, a concrete

rubble structure along the northeastern 100 m of the site, and a smaller wooden groin to the southwest. A detailed report of the geomorphology of Fort Wadsworth is available from (Psuty et al. 2015a; Psuty et al. 2017b). The dominant sediment transport direction is variable, alternating from the northeast to southwest. Three monuments have been established along the ocean-facing shoreline of Fort Wadsworth (Figure 70). The location, description, and coordinates of the Fort Wadsworth monuments are detailed in a booklet prepared for this purpose (Psuty et al. 2010e).



Figure 70. Site of coastal topography profile at Fort Wadsworth within the Staten Island Unit, Gateway National Recreation Area.

Annual Topography Change

The profiles along Fort Wadsworth were not as heavily impacted as sites with greater exposure to ocean waves (Figure 71 and Figure 72). In the Spring 2012 to Spring 2013 comparisons, all three profiles gained cross-section area in both the dune and beach feature (Table 23). Post-storm, the most drastic change was the construction of an artificial berm on FW3 that has remained stable through the Spring 2017 survey. The foredune crest of the constructed berm was +25 m seaward of the pre-construction foredune crest in Spring 2013. In general, post-storm, the three profiles were relatively stable with small variations in beach and dune cross-section area.

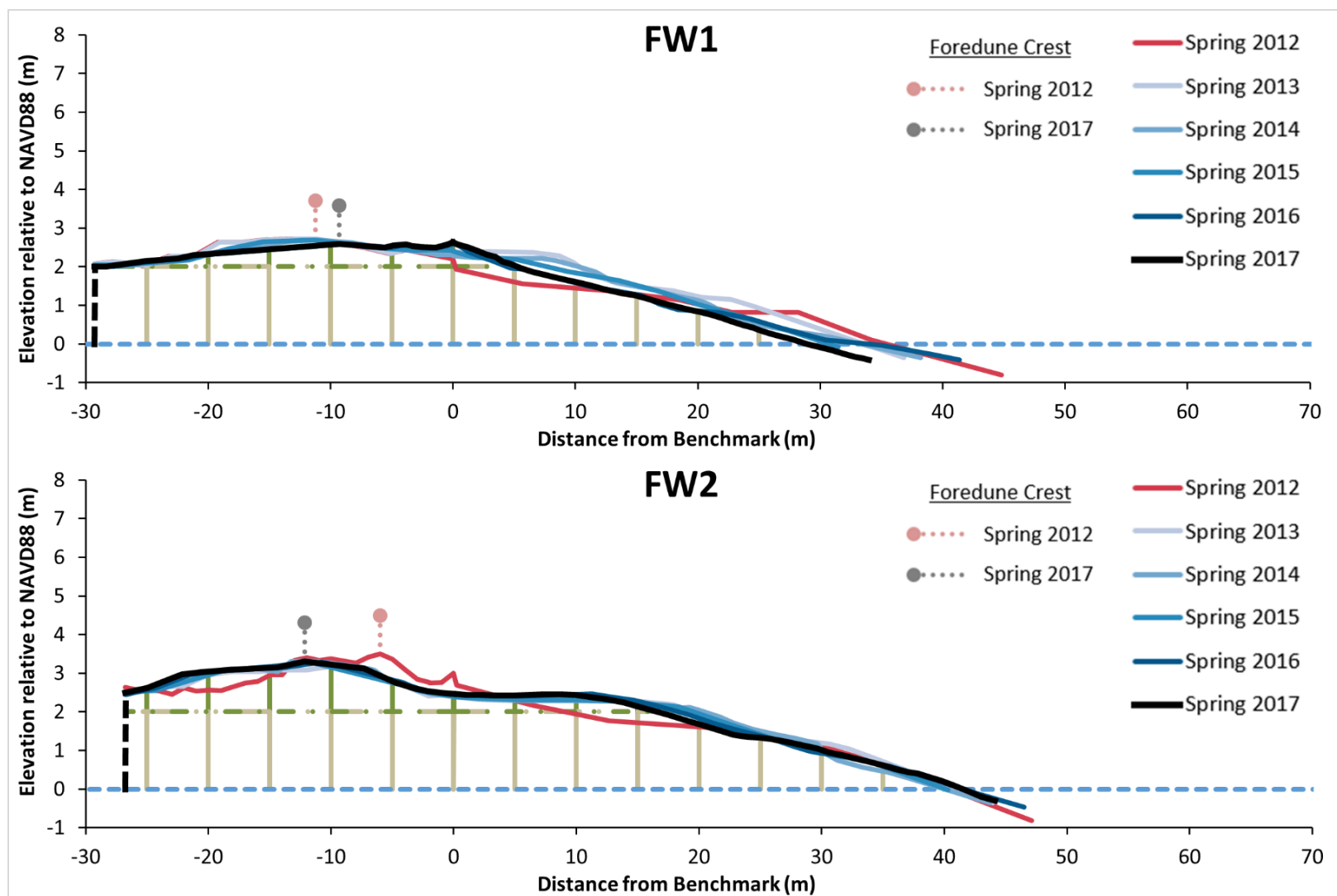


Figure 71. Coastal topography of Profiles FW1 and FW2 at Fort Wadsworth, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

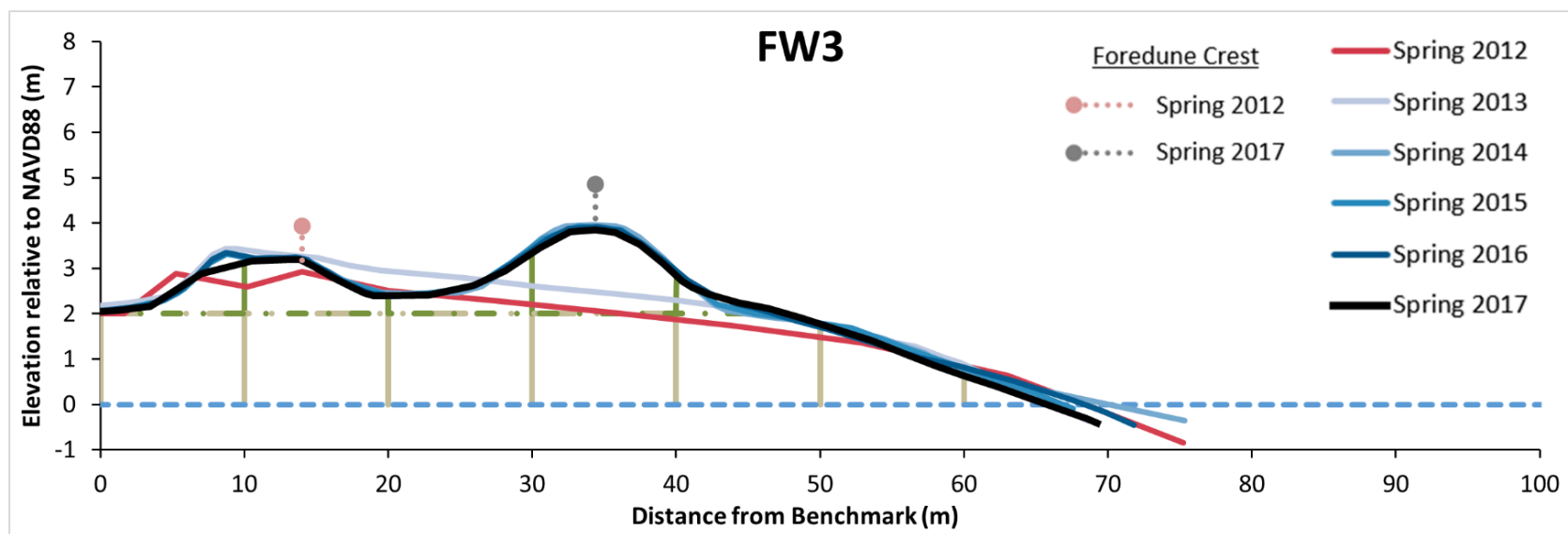


Figure 72. Coastal topography of Profiles FW3 at Fort Wadsworth, Gateway National Recreation Area. Foredune crest location at initial and most recent survey represented by a dot and dashed line, color coded respectively.

Table 23. Annual change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Fort Wadsworth, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012-Spring 2013	FW1	-1.75 \pm 0.03	0.14 \pm 0.03	0.00 \pm 0.06	9.58 \pm 3.61	3.71 \pm 1.97	5.87 \pm 1.69
	FW2	0.65 \pm 0.03	18.43 \pm 0.03	-1.15 \pm 0.06	5.73 \pm 3.82	1.00 \pm 2.34	4.73 \pm 1.52
	FW3	-2.93 \pm 0.03	-5.32 \pm 0.03	0.41 \pm 0.06	12.91 \pm 3.79	11.72 \pm 2.30	1.18 \pm 1.54
Spring 2013-Spring 2014	FW1	-0.32 \pm 0.03	0.25 \pm 0.03	-0.02 \pm 0.06	-6.36 \pm 3.55	-2.70 \pm 2.24	-3.66 \pm 1.31
	FW2	-0.99 \pm 0.03	1.11 \pm 0.03	-0.07 \pm 0.06	-1.26 \pm 3.81	0.90 \pm 2.64	-2.15 \pm 1.16
	FW3	4.58 \pm 0.03	25.53 \pm 0.03	0.62 \pm 0.06	14.62 \pm 3.84	12.41 \pm 2.53	2.21 \pm 1.32
Spring 2014-Spring 2015	FW1	-2.60 \pm 0.03	-0.46 \pm 0.03	-0.01 \pm 0.06	-1.22 \pm 3.47	-0.30 \pm 2.16	-0.93 \pm 1.30
	FW2	0.10 \pm 0.03	-25.14 \pm 0.03	1.00 \pm 0.06	0.74 \pm 3.78	-0.86 \pm 2.64	-0.17 \pm 1.14
	FW3	-3.22 \pm 0.03	1.99 \pm 0.03	-0.11 \pm 0.06	-0.49 \pm 3.88	-0.21 \pm 2.55	-0.28 \pm 1.33
Spring 2015-Spring 2016	FW1	3.13 \pm 0.03	2.62 \pm 0.03	-0.10 \pm 0.06	-4.69 \pm 3.48	-1.17 \pm 2.00	-3.52 \pm 1.49
	FW2	1.34 \pm 0.03	0.80 \pm 0.03	0.02 \pm 0.06	1.09 \pm 3.82	2.39 \pm 2.58	-0.21 \pm 1.24
	FW3	1.51 \pm 0.03	-1.70 \pm 0.03	0.06 \pm 0.06	0.27 \pm 3.83	0.57 \pm 2.61	-0.30 \pm 1.22
Spring 2016-Spring 2017	FW1	-4.91 \pm 0.03	-0.61 \pm 0.03	0.00 \pm 0.06	-1.00 \pm 3.43	0.82 \pm 1.93	-1.82 \pm 1.51
	FW2	0.02 \pm 0.03	-1.39 \pm 0.03	0.02 \pm 0.06	-1.24 \pm 3.86	0.06 \pm 2.50	-0.62 \pm 1.36
	FW3	-2.63 \pm 0.03	-0.12 \pm 0.03	-0.06 \pm 0.06	-3.83 \pm 3.80	-2.17 \pm 2.67	-1.66 \pm 1.13

5-year Topography Change

From Spring 2012 to Spring 2017, there was a gradient from northeast to southwest of cross-section area gain (Figure 73, Table 24). FW1 lost cross-section area, and FW2 and FW3 gained cross-section area. This indicated the dominant sediment transport direction during the survey period was to the southwest, matching the effects on the Miller Field profiles. However, FW3 also gained cross-section area due to construction of an artificial berm in 2013, and heavily influenced the trend of cross-section area gain from northeast to southwest. FW2 was the only profile to have the intersection with NAVD88 move seaward.

Table 24. Net change metrics of distance to NAVD88, distance to foredune crest, elevation of foredune crest and cross-section area at Fort Wadsworth, Gateway National Recreation Area.

Time Period	ID	Δ Distance (m)		Δ Elevation (m)	Δ Cross-section Area (m ²)		
		NAVD88	Foredune Crest	Foredune Crest	Total	Dune	Beach
Spring 2012-Spring 2013	FW1	-6.45 \pm 0.03	1.93 \pm 0.03	-0.12 \pm 0.06	-3.69 \pm 3.48	0.37 \pm 1.81	-4.05 \pm 1.70
	FW2	1.12 \pm 0.03	-6.18 \pm 0.03	-0.18 \pm 0.06	5.06 \pm 3.83	3.48 \pm 2.25	1.58 \pm 1.60
	FW3	-2.69 \pm 0.03	20.38 \pm 0.03	0.92 \pm 0.06	23.48 \pm 3.80	22.32 \pm 2.40	1.16 \pm 1.48

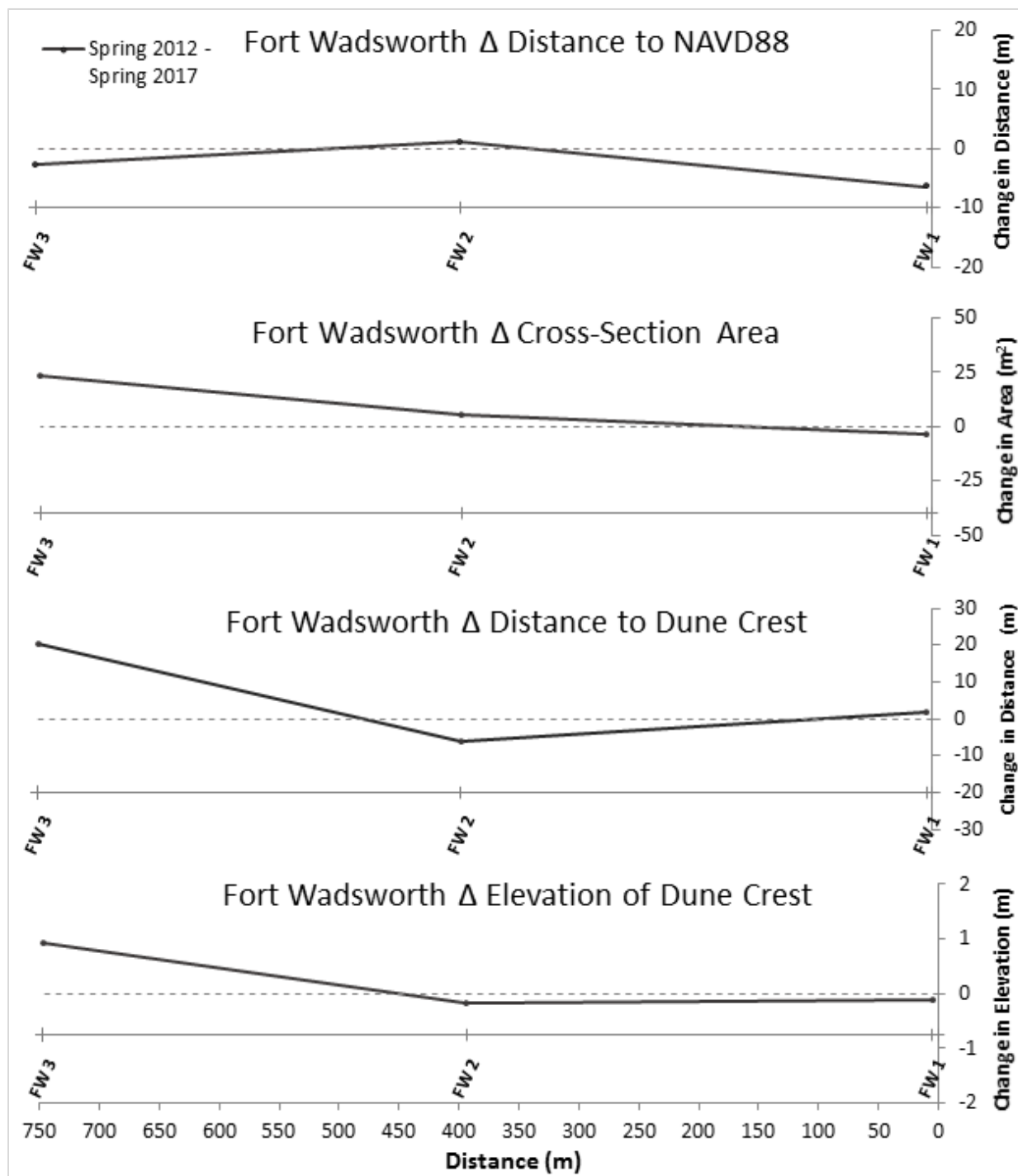


Figure 73. Alongshore dimensions of selected topographical variables at Fort Wadsworth within the Staten Island Unit, Gateway National Recreation Area, from Spring 2012 – Spring 2017, incorporating dune/beach profile sites.

Interpretation of Trends

Though inherent temporal variation in shoreline position and coastal topography renders 5 years to be a relatively short period of measurement, analysis of the GATE shoreline and topographical change from 2012 to 2017 provides a preview for future patterns and trends of change. The main variables that influenced the trends of shoreline change and coastal topography within GATE during the 5-year survey period were site exposure, natural impacts (storminess), and anthropogenic modifications (beach nourishment, structures, etc.).

Hurricane Sandy, October 2012, caused landward displacement of all GATE shorelines and effected all profiles within GATE. Sites with exposure to ocean waves were more heavily impacted, with erosion of the shoreline, elimination of the foredune, and greater loss of cross-section area (Sandy Hook Oceanside, Breezy Point Oceanside, Great Kills Oceanside). The Sandy Hook and Great Kills Oceanside shorelines never fully recovered from the landward displacement caused by Hurricane Sandy and persistently in the post-storm period. Sites such as Miller Field, Fort Wadsworth, and the bayside components of Sandy Hook, Breezy Point, and Great Kills were also impacted by Hurricane Sandy, but to a lesser extent due to their sheltered nature. Whereas these sites did not immediately recover post-storm, each of the shorelines fully recovered to its pre-storm mean shoreline position by Spring 2015. Post-storm, the coastal profiles within the sheltered sites have remained relatively stable. However, both Breezy Point Bayside and Sandy Hook Bayside profiles continued to erode, perhaps due to structures impacting sediment transport.

Post-Hurricane Sandy recovery was not measurable at Plumb Beach because a major nourishment event concluded just prior to the hurricane. The erosive trend continued at Plumb Beach eroding portions of the 2012 fill, leading to a scarp in the beach feature. The landward displacement of the shoreline in the Western Portion of the Plumb Beach site, post-nourishment, was greater than the landward displacement of the shoreline in the Western Portion of the site, pre-nourishment (Psuty et al. 2016e).

Anthropogenic modifications played a role in the recovery of the shoreline position and beach and dune features post-storm. Large nourishment projects updrift of Sandy Hook and Breezy Point added new sediment into the system, leading to seaward displacement of the shoreline and gains in cross-section area in the beach feature especially. The nourishment events that occurred updrift of Sandy Hook caused episodic seaward displacements of the shoreline but were not enough to bring the shoreline back to its pre-storm position. However, a large nourishment event updrift of Breezy Point Oceanside displaced the shoreline seaward of its pre-storm position, aiding in a full recovery. Whereas the shoreline and beach feature have recovered within Breezy Point Oceanside, the dune feature has not regained the cross-section area lost during Hurricane Sandy. Sites where structures limited the transport of sediment downdrift, such as at Great Kills and downdrift of the eastern groin at Plumb Beach, were eroded continuously throughout the 5-year and 4-year periods (post nourishment), respectively. This is evident in both the landward displacement of the shoreline and in the loss of cross-section area on the profiles within the sites.

Of all the GATE sites, Breezy Point Oceanside and, to a lesser degree, Breezy Point Bayside, were the only sites with a positive trend in shoreline displacement and cross-section area gain in the beach over the entire survey period. Major contributors to the gain at Breezy Point Oceanside were nourishment events at and updrift of Jacob Riis Park. However, this trend of recovery and accretion only applies to the shoreline and the beach topography feature, where sediment can easily be remobilized. Variation in sediment budget caused by structures and anthropogenic manipulations of sediment supply, impacts of storm events, and shoreline exposure were major drivers of shoreline position and topographical change during the 2012 – 2017 period.

Trends of Full Shoreline Dataset

In order to enhance understanding of long term shoreline change trends within GATE, the shorelines within the previous trend report (Psuty et al. 2016e) were compared to the 2012 to 2017 dataset. The rates of shoreline displacement were more negative during the 2012 to 2017 reporting period for all sites within GATE except for Breezy Point Oceanside and Great Kills Bayside. Sandy Hook, Plumb Beach, Great Kills Oceanside, Miller Field and Fort Wadsworth all had positive net displacement rates previously that changed to negative landward displacement rates for the 2012 to 2017 period. This change in rate was largely due to large landward displacements caused by Hurricane Sandy and lack of recovery post-storm. Breezy Point Bayside had a positive net displacement rate during both reporting periods, though the 2012 to 2017 rate was less positive. Great Kills Bayside had very similar positive displacement rates both pre- and post-2014 dredging event, indicating consistent seaward displacement of the shoreline, and future need of dredging if seaward displacement continues. Breezy Point Oceanside had a small positive net displacement rate during the previous reporting period and a large positive net displacement rate during the 2012 to 2017 reporting period. This is again due to the 2014 nourishment episode adding sediment into the system. The Fall 2016 and Spring 2016 net displacement values are not as positive, perhaps indicating a return to a more erosional trend.

Information for Management and Recommendations

At Plumb Beach, the shoreline seaward of the Belt Parkway has continued to erode despite anthropogenic manipulation including placement of stone structures and a major nourishment event. The emplaced fill has eroded causing a scarp in the beach face. The area that poses the greatest threat to the Belt Parkway is the erosion updrift and downdrift of the breakwater, albeit the greatest erosion occurred downdrift of the eastern groin. Compared to the erosion at Plumb Beach in the first Trend Report, the eastern extent of the eroding shoreline has expanded to include an additional 250 m of shoreline downdrift (Psuty et al. 2016e). The greatest erosion at Great Kills occurred at the western margin and downdrift of the protruding headland in the northeast. Park infrastructure in this area including the parking lot and adjacent road are at risk due the consistent erosion of the shoreline and inland displacement of the bluff edge. Within Sandy Hook, the area near Fishing Beach had the largest amount of erosion in the shoreline and beach feature. The shorelines and profiles at Miller Field and Fort Wadsworth have remained stable and pose no threat to nearby infrastructure.

As is true for many coastal areas, the positive and negative changes are being driven by the availability of sediment. Whether the result of unscheduled natural impacts or planned anthropogenic manipulations, the shoreline position and coastal topography are responding to the local sediment supply and sediment budget. Some changes are just part of the natural variation. Other changes are in response to human actions and can be predicted with the knowledge gained through this monitoring. Importantly, armed with knowledge of the past responses to the variety of manipulations, management can anticipate and adjust to the potential impacts at determined locations within the park.

Changes to the Protocol

There are no documented changes to the protocol used in the data collection cited in this report.

Problems/Concerns

The gaps in shoreline position data during certain surveys analyzed in this report reduce the comparability of shoreline position data from season to season and year to year. Statistics calculated with incomplete data sets are either flagged (Table 4, Table 6, Table 7), or portions of the shoreline represented in every survey must be extracted from the full data sets for analysis. Despite these efforts, gaps in shoreline position data result in a skewed analysis that must be taken into consideration when viewing some of the results of this report. There were also data gaps in the coastal topography profiles due to issues with equipment or issues accessing the survey areas. Profiles missing a Spring survey use either Fall survey data to complete an annual comparison or use LiDAR data, noted in affected sections. In the future, better communication between management and surveyors about beach closings for bird nesting would allow for improved survey planning and lessen data gaps in both shoreline data and coastal topography data.

Data Archives

The lines that represent the shoreline position for each of the surveyed periods are stored as features in a Geodatabase along with the Transects and Baseline used in the shoreline change analysis, and the spreadsheet with the results from the DSAS analysis. Coastal Topography data is stored as the raw data files and processed .csv files with northing, easting and elevation data. This information and data are available from the Data Manager for the National Park Service, Inventory and Monitoring Program, Northeast Coastal and Barrier Network:

Data Manager, Northeast Coastal and Barrier Network

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